AD-A019 852

A STUDY OF THE EFFECT OF PERIPHERAL VISION MOTION CUES ON ROLL AXIS TRACKING

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December 1975

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER GE/EE/75-37	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A STUDY OF THE EFFECT OF PERIPHERAL VISION MOTION CUES ON ROLL AXIS TRACKING		5. TYPE OF REPORT & PERIOD COVERED MS Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Don R. Price Captain		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS System Technology Branch/ Environmental Medicine Division (EMT) Aerospace Medical Research Laboratory Wright-Patterson AFB, Ohio 45433		12. REPORT DATE December, 1975
		13. NUMBER OF PAGES 112
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17
Jerry C. Hix
JERRY C. HIX, Captain, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Display Devices	Human Factors
Peripheral Display	Peripheral Vision
Peripheral Stimuli	Visual Motion Cues

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Six subjects were used as controllers for an experiment in which conpensatory roll axis tracking was performed with and without the presence of peripheral vision motion cues. Two different controlled plant dynamics, of the general forms K/S and K/S^2, were simulated on an analog computer. Control was commanded via a force stick located in a stationary fighter aircraft cockpit mock-up. Controlled plant roll rate, in the form of vertically moving black and white grid lines, was displayed on two 21-inch television

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Findings of the experiment show that for marginally stable plants of the general form K/S^2, roll axis tracking is improved when plant roll rate information is provided in the peripheral field of vision. Performance is not significantly improved by the display when the controlled plant is stable and of the general form K/S. The peripheral display improves performance with marginally stable plants by providing instantaneous plant rate information which must, otherwise, be obtained by computing derivatives from the central error display. The human controller's computational workload is reduced, permitting more precise response to any additional lead compensation necessary to properly follow the input signal.

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

by

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December 1975

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Preface

The research effort presented in this report was sponsored by the Environmental Medicine Dividion of the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio. It is the author's sincere hope that results of this study will add to the knowledge of peripheral vision system capabilities and limitations for improving human operator performance of manual control tasks.

I would like to express my deep gratitude to my thesis advisor, Captain Thomas E. Moriarty, for the guidance and advice he provided during the study. I would also like to thank Major James D. Dillow for his invaluable suggestions and assistance while planning and designing the procedures for this research effort.

I wish, also, to express my deep gratitude to Mr. Andrew M. Junker of the Aerospace Medical Research Laboratory for the technical advice and support he provided throughout the investigation. Special thanks are extended Mr. James S. Ater and Mr. Robert McIntyre for their eager assistance in conducting the daily experimental sessions.

My special appreciation is extended to my wife, Julie, for her patience, understanding, and encouragement during the period of this study.

Contents

List of Figures

List of Tables

Notation

Y_C	Controlled plant transfer function
Y_S	Subject describing function
Φ_M	Phase margin
Φ_{cc_c}	Correlated stick power spectrum
Φ_{cc_r}	Remnant stick power spectrum
Φ_{ee_c}	Correlated error power spectrum
Φ_{ee_r}	Remnant error power spectrum
ω_C	System gain crossover frequency

Abstract

Six subjects were used as controllers for an experiment in which compensatory roll axis tracking was performed with and without the presence of peripheral vision motion cues. Two different controlled plant dynamics, of the general forms K/S and K/S^2, were simulated on an analog computer. Control was commanded via a force stick located in a stationary fighter aircraft cockpit mock-up. Controlled plant roll rate, in the form of vertically moving black and white grid lines, was displayed on two 21-inch television screens positioned on either side of the cockpit. The target aircraft's motion was simulated by a sum-of-sines input forcing function. RMS error scores and time histories were recorded for individual runs. Frequency domain analysis and data averaging techniques were used to study and compare subject performance.

Findings of the experiment show that for marginally stable plants of the general form K/S^2, roll axis tracking is improved when plant roll rate information is provided in the peripheral field of vision. Performance is not significantly improved by the display when the controlled plant is stable and of the general form K/S. The peripheral display improves performance with marginally stable plants by providing instantaneous plant rate information which must, otherwise, be obtained by computing derivatives from the central error display. The human controller's computational workload is re-

duced, permitting more precise response to any additional lead compensation necessary to properly follow the input signal.

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I. Introduction

Background

Information transfer properties of the human operator's peripheral vision system have recently emerged as a major area of interest to researchers and design engineers in the field of aerospace manual control systems. Much of the work has been prompted by modern advances in aerospacecraft technology, increased emphasis on improving mission simulation capabilities, and the need to more accurately account for peripheral vision effects in pilot modelling predictive schemes.

One body of the overall research effort is directed toward investigating the capabilities of peripheral vision for improving information transfer to human operators involved in complex control tasks. This effort is, in part, due to recent advances in aerospacecraft capabilities which have required the pilot to perform an increasing number of control tasks based on visual information provided at the center of his field of view. As task loading is increased, a point is reached where the human controller cannot process and react in time to additional information displayed in his central (foveal) field of vision. In the last ten years, research has been performed which indicates that peripheral vision cues might be used to assist in accomplishing manual control tasks (Ref 1:12-31)(Ref 2:199-204). This thesis is in support of this area of research.

Motion as a Peripheral Vision Stimulus

Early studies on the use of peripheral displays used brightness change as the mode of peripheral stimulus. Since a differential brightness may prove satisfactory only under relatively low or moderate levels of ambient illumination, recent effort has been directed toward using peripheral vision motion stimulus to assist the human operator in accomplishing control tasks. In describing how the eye sees movement, Gregory stated that motion is detected by receptors in the eye which are sensitive only to changes in illumination. Those receptors respond to the leading and trailing edges of moving images, but will not signal the presence of stationary images unless the eyes are moving (Ref 3:98). Results of recent stroboscopic movement experiments by Pantle suggest the existence of two human vision motion channels with different functional properties. The investigation indicated the presence of one motion channel with a low- and one with a high-pass temporal frequency response (Ref 4:27-36).

In 1967, after reviewing significant findings of research concerning peripheral vision and after conducting experiments of his own, Vallerie concluded that a velocity display involving motion would be satisfactory under a wide range of illumination. In an earlier investigation, Kobrick determined that response times are lowest in the area adjacent to a plane passed through the line of sight that is defined by the two eyes and the point of fixation; and that along this plane, from the center of the fovea vision to the edge of the peripheral vision, there is little difference in response time to a stimulus (Ref 5:7). McColgin reported that the ability to perceive vertical movement as compared with horizontal movement is slightly better in this area (Ref 6:779).

A study of the previous experiments and findings indicates that certain types of visual motion cues displayed in the peripheral field of vision might improve a human operator's control performance. Furthermore, rate information presented as vertical movement of images possessing sharp edge definition would appear to be a good choice as the peripheral vision stimulus.

Goal

The goal of this research effort is to determine if a stationary operator's performance of roll axis tracking is improved when controlled plant roll rate, in the form of vertically moving black and white grid lines, is displayed in the human operator's peripheral field of vision. Implicit in this goal is a study of the operator's control strategy and frequency domain analysis of the man-machine performance characteristics.

Research Description and Scope

Two different controlled plant dynamics were simulated on an EAI 580 analog computer with control commanded via a force stick located in a stationary fighter aircraft cockpit mock-up. Controlled plant roll rate in the form of vertically moving black and white horizontal grid lines was provided as a peripheral vision display on two 21 inch Conrac television screens. Both male and female controllers were used as subjects for an experiment in which roll axis tracking was performed with and without the presence of the peripheral vision motion cues.

The roll-axis tracking task chosen for the subjects was a compensatory tracking task. The target aircraft's motion was simulated by a sum-of-sines input forcing function generated on a PDP-11 digital computer.

Time histories of the input, control, error, and plant signals were recorded for individual runs. Frequency domain and data averaging techniques were used to compute power spectrums and generate describing functions in order to study and compare subject control strategies and performance. The use of a sum-of-sines input forcing function greatly facilitated the identification and treatment of the human controller's correlated and remnant responses.

Organization

The contents of this thesis are divided as follows:

The definitions and fundamental concepts associated with the experiment design and frequency domain analysis are discussed in Chapter 2. Chapters 3 and 4 present a description of the experiment and the experimental procedure, respectively. The form of the experimental data and the methods to be used in data analysis are given in Chapter 5. Chapter 6 contains the results of data analysis using the procedures and techniques discussed in Chapter 5. Chapter 7 presents the conclusions and recommendations for further study.

II. Basic Concepts

This chapter presents fundamental definitions and concepts that are important to the experimental design and analysis approach of this thesis. Also presented are some of the statistical considerations which dictate the particular methodology utilized.

Quasi-linear Model

Experiments have verified that human operators of manual control systems responding to random-appearing visual forcing functions, exhibit a type of behavior which is analogous to the behaviour of equalizing elements inserted into a servo system to improve the over-all dynamic performance. In essence, the human controller attempts to adopt a control strategy that will result in closed loop performance comparable to that of a good feedback control system. For actual measurement situations, the time varying non-linear human controller can be represented by a quasi-linear model.

The quasi-linear model is an equivalent engineering mathematical description for nonlinear control elements in which the relationships between some pertinent measures of input and output signals have "linear-like" features for fixed input conditions. An equivalent linear element, characterized by a describing function, is used to account for the linear portion of the response. The component of the response left over from that represented by the linear element is called remnant. A discussion of the quasi-linear approach is contained in the excellent report of McRuer et al (Ref 7:7-28).

Human Controller Remnant

Human controller remnant has generally been defined as the portion of the controller's response that is not accounted for by his describing function. Remnant, in the context of this thesis, is defined more specifically as the portion of the human controller's response not linearly correlated with the system input forcing function. This definition of remnant is commonly called the "closed-loop remnant" and permits a meaningful analysis of human performance of a compensatory tracking task when the possibility exists of large amounts of remnant-induced power circulating around the control loop (Ref 8:4). Furthermore, when input signals are constructed from sinusoidal components, the remnant-induced power is assumed to vary continuously with frequency in the vicinity of input frequencies and to vary smoothly through the input frequencies. These assumptions are consistent with previous findings of McRuer et al. (Ref 7:127) and the work of Levison and Kleinman (Ref 8:8-14).

Jex et al., in their review and study of remnant sources and remnant modelling, state that for a closed loop manual control task, the many diverse remnant contributions blend into a fairly wideband stationary random process. In particular, for remnant which arises from perception of continuous signals presented on a visual display in a manner similar to the foveal display of this study, the wideband low frequency noise has a fairly flat spectrum in the input bandwidth (Ref 9:8-9). These observations can be incorporated into a comparative study of error signal remnant power spectra.

Sum-of-Sines Tracking Input

A popular tenet of many manual control system research engineers is that a judicious combination of sinusoids can provide a system forcing function that appears to be stochastic to a human controller. A choice of this type of signal as a tracking input overcomes many of the measurement difficulties associated with inputs that are continuous in frequency.

If each component frequency of the input is generated without distortion and is harmonically related to the reciprocal of the run length, then the Fast Fourier Transform (FFT) of the input signal will contain power only at the nominal input frequencies. Since there is no input power at non-input frequencies, the power at non-input frequencies (excepting system noise) is by definition remnant power. If the assumption that remnant power varies smoothly and continuously is valid, remnant power at a nominal frequency can be determined by averaging across a frequency band on either side of (but not including) the nominal frequency.

The number of sinusoidal components in the tracking input must be sufficient to cause the subject to track the input as if it were truly random process. There is a practical upper limit to the number of component sinewaves employed, however, as the advantage of highly concentrated input power is reduced as more input frequencies are added. Levison states that tracking inputs composed of five sinusoids have proven to be sufficient; while as many as 13 sinusoidal components, spaced at frequency intervals of approximately 1/4 octave, have been successfully utilized in laboratory studies (Ref 10:10).

The Human Visual System

A general understanding of the physiological functioning of the human visual system is necessary before attempting a study of the information transfer capabilities of man's peripheral visual channel.

The first stage of human visual sensation is the eye structure called the retina - a thin sheet of interconnected nerve cells, including light-sensitive photoreceptor cells called rods and cones. Light travels through layers of blood vessels, nerve fibers, and supporting cells to the rod and cone cells which function independently to convert light into electrical pulses - the coding required by the brain. The cones function under reasonably bright conditions (greater than about 0.1 to 10 foot-lamberts) and provide both color and detail information (photopic vision). The rods function at low illumination levels giving vision in shades of gray with very little or no detail (scotopic vision)(Ref 3:44-48).

The outputs of the photoreceptor cells - there are approximately 125 million rods and cones in each eye - are transmitted to the reception areas of the brain via the optic nerve which consists of approximately one million individual channels insulated from each other and bundled together. Since only one million channels are available to transmit data from the 125 million receptors to the brain, some calculation and data reduction must occur directly in the retina (Ref 11:17). The placement of the rods and cones in the retina and the manner in which the photoreceptors are connected to the optic nerve channels results in two fairly distinct visual regions - the fovea or central visual region characterized by high acuity and color vision and the peripheral visual region which includes the remainder of the visual field.

The central foveal area comprises roughly two degrees of the total visual range of approximately 180 degrees horizontally and 60 degrees vertically (Ref 11:18). The fovea contains primarily cone receptors and provides high acuity photopic vision as a result of a one-to-one correspondence between fovea receptors and optic nerve channels. The human being is aware of much more than a two degree field of photopic vision, however, because the eye rapidly scans the entire field of interest.

The photoreceptors of the peripheral retina, in contrast with the fovea, consist of both rods and cones connected in groups to a single nerve cell. The outputs of the photoreceptors in each separate group are processed directly in the retina and relayed into a single optic nerve channel.

As a result, this preprocessed peripheral visual information sent to the brain primarily concerns movement of the objects which are not being looked at through the sharp foveal vision. Although color and form data are very poor, the rods function to provide scotopic vision in the peripheral at low levels of illumination (Ref 11:18-19)(Ref 1:35-37).

When compared with the foveal system, peripheral vision offers some distinctly different information transfer properties. The peripheral visual field is much larger and inputs are received from all directions simultaneously. Scanning is not necessary. Vallerie proposed the concept that the foveal and peripheral visual channels operate as independent parallel channels of information but cannot be attended to simultaneously (Ref 1:8). Senders and Vernon, however, determined that the frequency of attention switching between channels may be sufficiently high that an apparent simultaneity of information processing results (Ref 12:4)(Ref 13:211-212).

Peripheral Motion Cue Detection Limits

In recent years, successful attempts to model the human controller using modern control and optimization theory have incorporated the assumption that the controller can extract position and rate information from a single display indicator. This assumption is based on remnant and psychophysical studies of human performance (Ref 14:359). Controlled plant roll rate information, in this research effort, is presented on peripheral vision displays in the form of vertical motion of black and white grid lines. If the assumption that the human controller can extract position and first derivative information from a single display extends to the peripheral vision field then, for design and analysis purposes, a knowledge of the peripheral motion cue detection range would be of value. The motion detection limits would identify the controlled plant rotational frequency bandwidth for which both controlled plant angular roll rate and acceleration information, displayed in the form of resultant linear velocity and acceleration, are available.

Motion Cue Threshold. Peripheral motion thresholds are of such an applied nature that none of the results from previous investigations could be used to predict an exact threshold value for the peripheral motion cues utilized in this study. The findings of three earlier experiments, however, are somewhat useful in approximating the expected threshold value.

In 1960, McColgin investigated the absolute velocity thresholds of movement at 48 positions in the binocular peripheral vision field under conditions of constant photopic lighting. Rotary shaft motion of an aircraft altimeter was converted with gears to linear motion and movement thresholds were determined for horizontal and vertical movement of an attached white altimeter hand which measured 0.1 in. wide and 1.13 in. long. The altimeter hand could move smoothly back and forth a distance of 1.37 inches. Ten airline pilots were used as subjects and were positioned such that the instrument face was 37.5 in. from the center point between the subject's eyes. The resulting absolute threshold isograms on a perimetric chart were elliptical in shape, with the horizontal axis approximately twice as long as the vertical axis (see Fig. 1). The data indicated that an individual's ability to perceive vertical motion is slightly better than his ability to perceive horizontal motion in the area adjacent to the horizontal axis (Ref 6:774-,78).

McColgin also investigated the absolute threshold at the 45 degree meridian as a function of the length of the horizontal instrument hand (see Fig. 2). Results indicated that

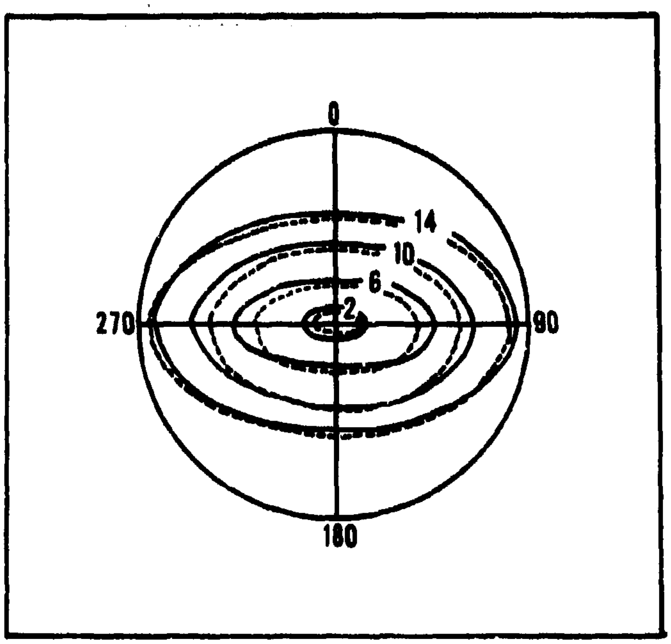

Figure 1. Perimetric Chart Showing Absolute Threshold Isograms of Linear Motion, in Strokes/Min. Vertical Motion is Represented by Solid Lines and Horizontal Motion by Dashed Lines (From Ref 6:776).

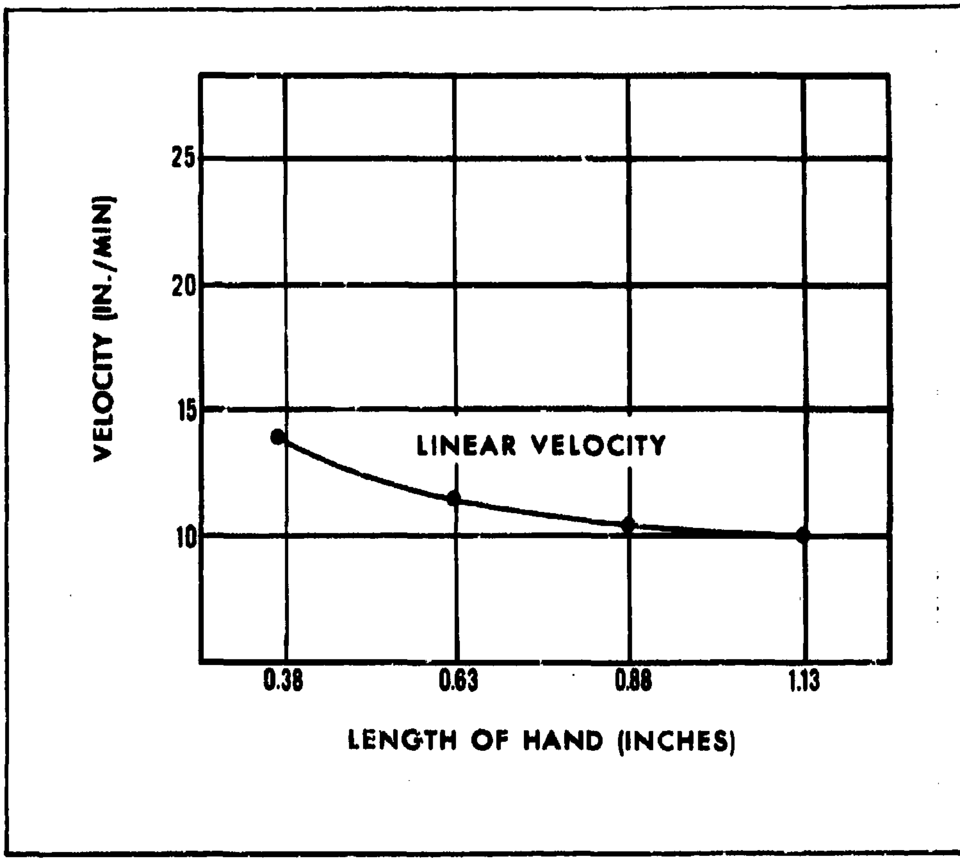

Figure 2. Absolute Thresholds at the 45-Degree Meridian on the 90 Degree Radial (From Ref 6:777)

the velocity and the area swept by the instrument hand are significant factors in the perception of movement with velocity being the more significant influence.

Investigating motion detection thresholds with the eyes fixed, Bhatia and Verghese observed that the threshold of detection as measured by the width of the object was not influenced by the variation in the height of the object (Ref 15:283-286). Their observation concerned horizontal movement, in the near periphery, of rectangular strips of different widths but uniform height. Bhatia and Verghese concluded that "the ability to detect a moving object is a function of the dimension of the object along its line of motion and is independent of the dimension perpendicular to its line of motion (Ref 15:284)." For their experimental conditions, Bhatia and Verghese observed that the threshold _angular_ size for detection of the test object varied with changes in the distance between the observer and the moving object, but the threshold _linear_ size of the object was constand and independent of the distance. Angular size and linear size were defined as measurements related to the dimension of the test object along its line of motion (width).

In 1972, Leibowitz _et al_. investigated motion thresholds as a function of stimulus eccentricity in which subjects maintained monocular fixation with their dominant (right) eye. Thresholds for motion perception were determined for the temporal visual field for a 1.0-second exposure at eccentric angles ranging from 0 degrees to 80 degrees. The stimulus was a white square, 1.3 cm on a side, with luminance 4.3 millilamberts, viewed against a black background at a distance of 78.7 cm. A typical threshold value of 1 minute of arc per second was found with foveal fixation, the motion threshold progressively increasing with increasing eccentricity. Motion sensitivity increased by only a factor of 10, however, over the range of the 80 degree arc (Ref 16: 1207-1208). All visual functions in the periphery were degraded, but motion suffered the least. Rogers, in a separate investigation, determined that for a moving image, there is no significant change in perceptual sensitivity for the peripheral image compared to the foveal image (Ref 2:203).

Fusion Speed. For the peripheral display used in this study, there exists a grid velocity above which the black and white grid lines appear as fused. Above fusion speed, only gross rate information is available to the controller. If the controller's strategy incorporates magnitude changes of the peripheral vision motion cues, then his overall strategy would necessarily be affected when the controlled plant roll rate resulted in grid velocities above fusion speed. If, however, the controller responds only to gross values of controlled plant angular velocities (and, possibly, accelerations), then determination of the display fusion speed would not be critical to analyzing the controller's performance in this experiment.

Previous investigations were not of such an applied nature as to permit a determination of the fusion speed for the peripheral display used in this study. A recent finding by Bhatia, however, is of some interest. Bhatia determined the values of critical separation at which two white bars on a black background appear as fused at distances of 2 and 5 meters at speeds ranging from 20 to 210 cm/sec (Ref 17:23-32). Unfortunately, the only region of the peripheral retina tested was 3 degrees above the fovea with the bars moving horizontally left to right. The height to width ratio of the white rectangular bars was, in all cases, 3:1 with the width of the bars varying from 1 mm to 48 mm. For each presentation of a given size bar, the gap width between bars equalled a single bar width; thus, the height and the total width of a test object were the same. Bhatia determined that the value of critical linear separation (gap width) of the white bars was independent of the distance between the observer and the object. For a gap of 35 mm (1.38 in.) the fusion speed was approximately 200 cm/sec (78 in/sec).

III. Experiment Description

This chapter presents the design of an experiment to investigate a stationary human controller's performance of a roll axis tracking task when controlled plant roll-rate information is prese ted in the controller's peripheral field of vision.

Tracking Task

The task was to follow a target aircraft in the roll axis. A manual closed-loop control system, incorporating a plant with roll axis dynamics simulated on an analog computer, control stick, stationary seat, and visual displays was assembled. Target aircraft dynamics were simulated by a sum-of-sines forcing function input to the system. The difference between the input roll angle a d the controlled plant position (ϕ_e) was presented to the human operator on a central visual display (Fig. 3) while controlled plant roll rate in-

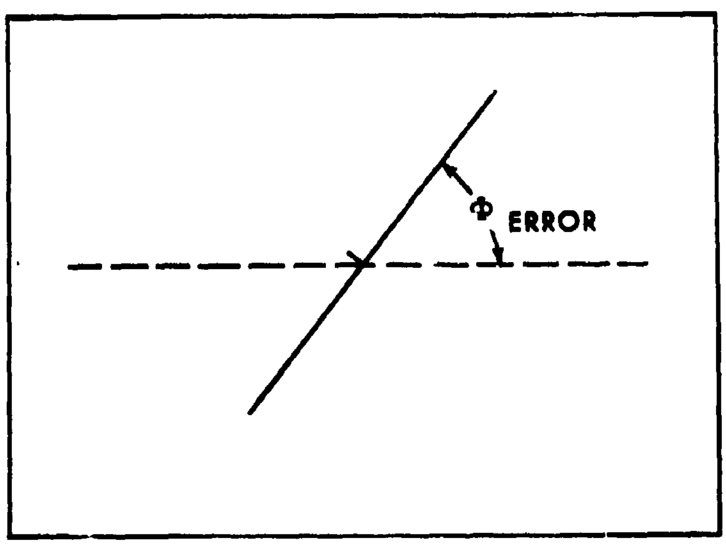

Figure 3. Central (Foveal) Display

formation was presented as a peripheral vision display. A block diagram of the roll axis tracking simulation is shown in Fig. 4. The human operator was told to minimize the error signal during each experiment run.

Controlled Plant Dynamics. Two different controlled plants were used in the experiment. The choice of plant dynamics permitted a comparision of peripheral vision motion cue effects on human operator control strategy for different levels of task difficulty. Plant No. 1 was programmed on an analog computer to yield a transfer function of

$$G(s) = \frac{135}{s(s + 1)(s + 10)} \tag{1}$$

and was considered to be an easy plant to control. The plant frequency response is shown in Fig. 5. Plant No. 2 was designed to be more difficult to control (Fig. 6). The transfer function of Plant No. 2 was

$$G(s) = \frac{63.75}{s\ (s^2 + 0.5)(s + 10)}. \tag{2}$$

The two controlled plant dynamics were similar to two of the plant dynamics used in an earlier motion effects study performed by Junker and Replogle (Ref 18:819-822).

Sum-of-Sines Tracking Input. A different sum-of-sines input signal was used with each of the two controlled plants. The compensatory tracking task was performed with Plant No. 1 and a sum-of-sines input forcing function of 1.25 radians/

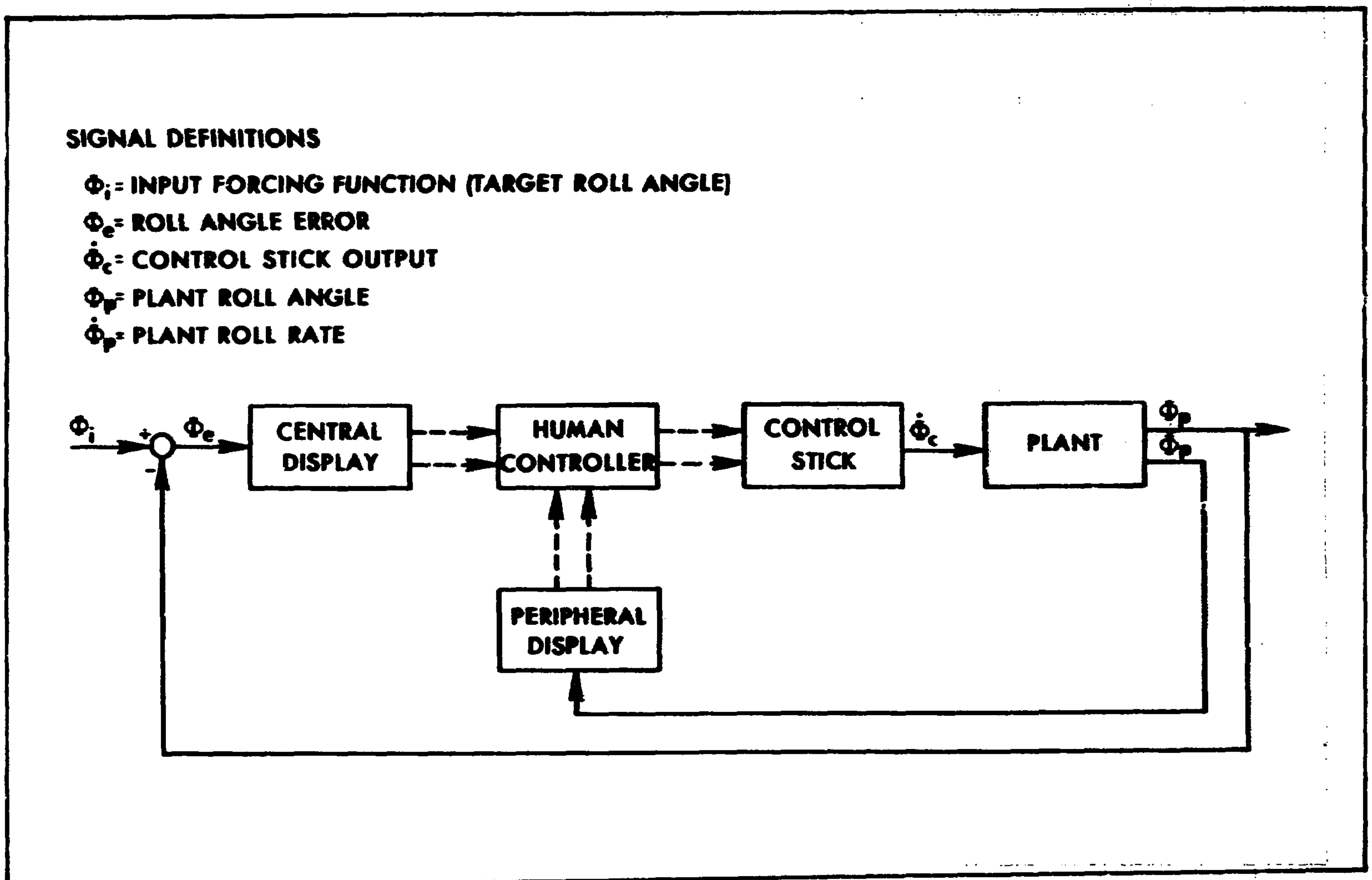

Figure 4. Simulation Block Diagram for Roll Axis Tracking Task

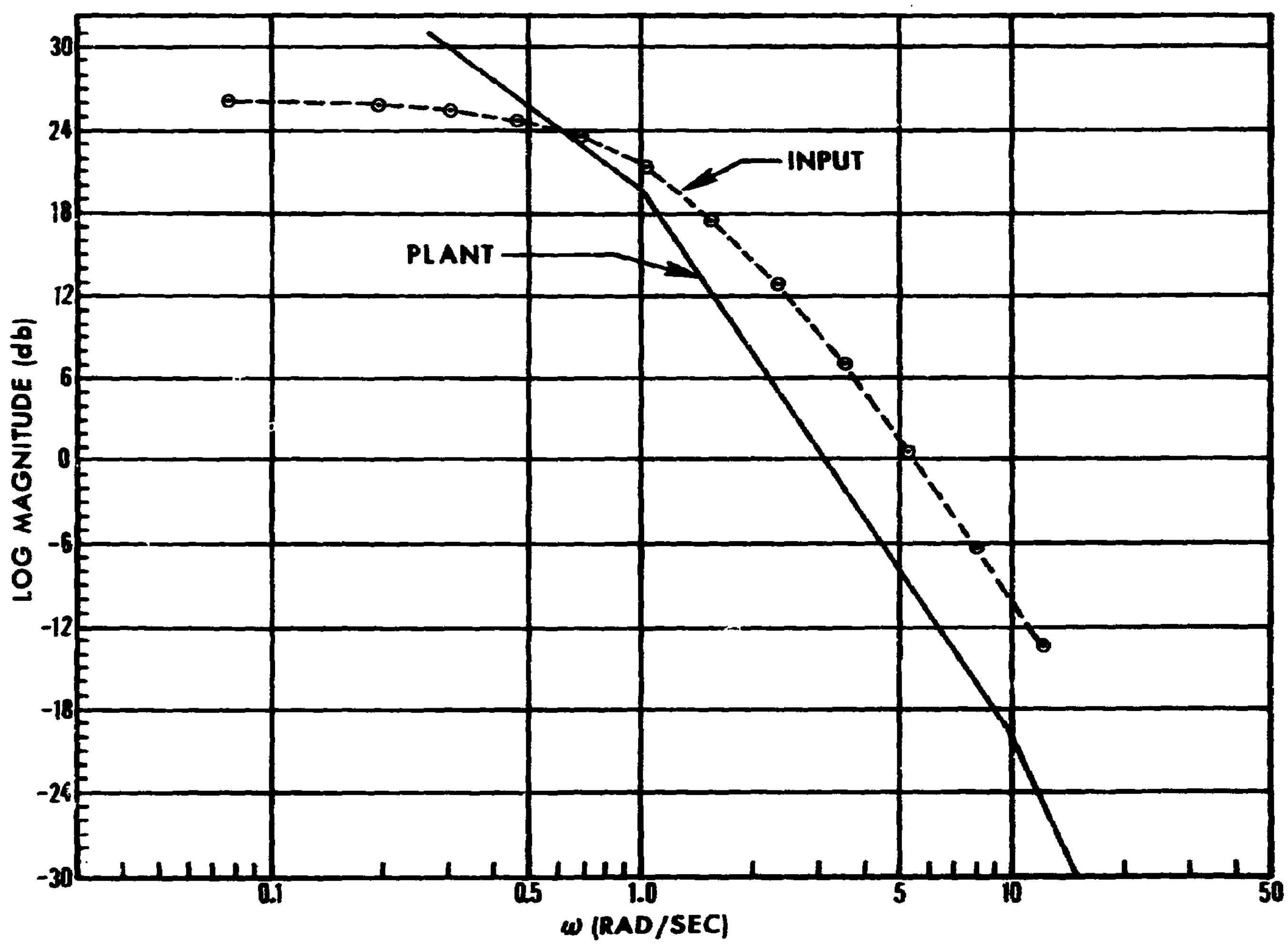

Figure 5. Plant No. 1 Frequency Response and Input Power Spectrum (Frequency Components Denoted by Circles)

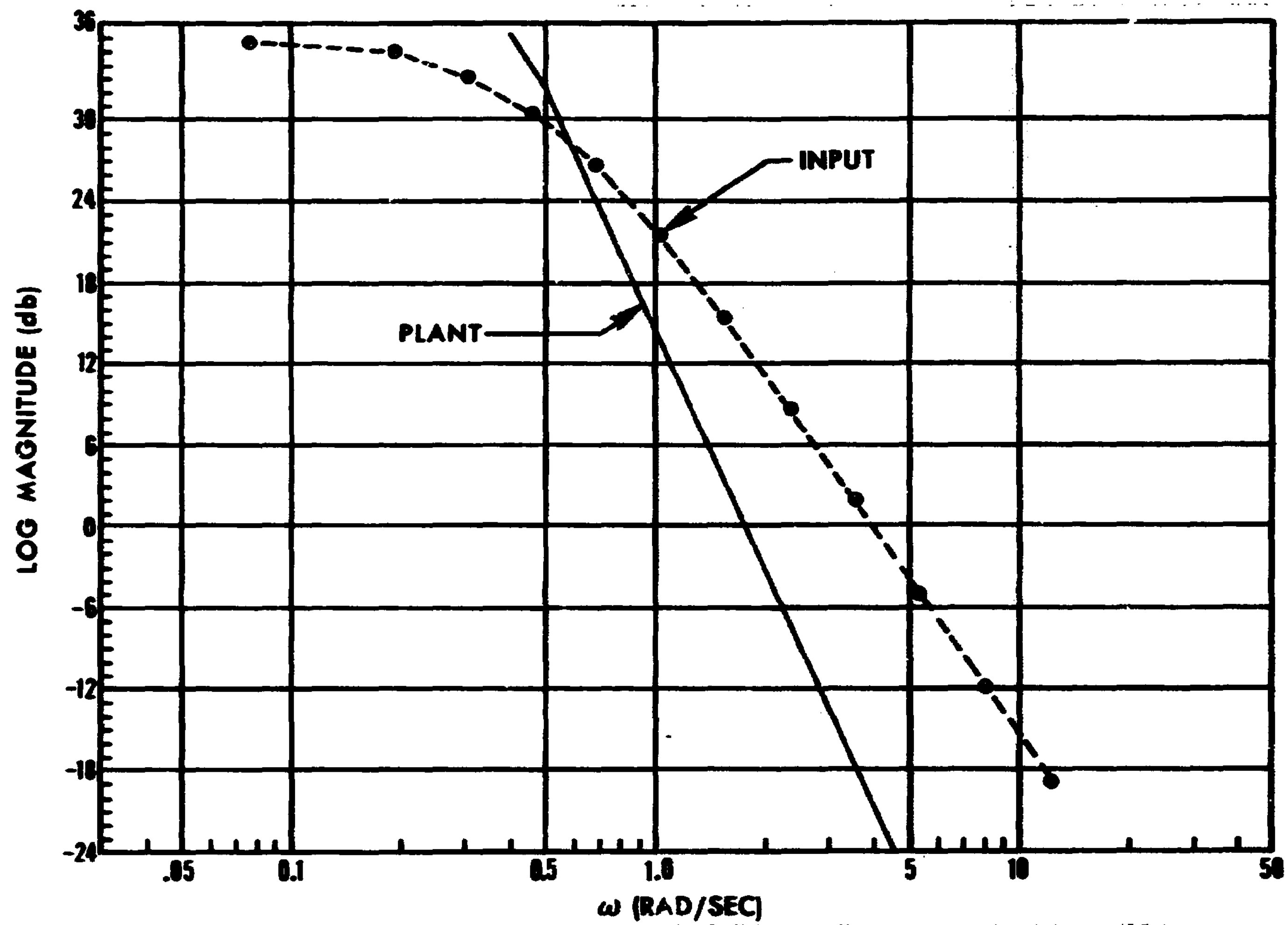

Figure 6. Plant No. 2 Frequency Response and Input Power Spectrum (Frequency Components Denoted by Circles)

sec bandwidth and 20 degree RMS amplitude (Fig. 5). The tracking input used with Plant No. 2 had a bandwidth of 0.5 radian/sec and an RMS amplitude of 40 degrees (Fig. 6). Each input signal consisted of 12 sinusoidal components and is detailed in Appendix A. The particular input signals selected for the experiment differed in tracking difficulty and resembled the zero mean bandlimited Gaussian noise tracking inputs used by Junker and Replogle in their motion effects study (Ref 17:819). The input signals were generated by a digital computer from a computer program.

Equipment and Facilities

The equipment used in the experiment basically consisted of two analog computers, a PDP-11 digital computer, two Wavetech signal generators, two 21-inch Conrac televisions, and a stationary fighter-type cockpit mock-up which included a side-mounted force stick and a Conrac television monitor that was centered in front of the seat. The two analog computers were used to program the controlled plant dynamics and to provide buffering between the simulated dynamics, control stick, and visual displays. The digital computer simulated a target aircraft by inputing the pre-programmed sum-of-sines forcing function to the system. The computer was also used to collect data from the experiment runs and perform frequency analysis computations. A circuit which included the two signal generators and 21-inch television supplied the peripheral cues; the centrally located Conrac television monitor displayed roll task error. The side-mounted force stick was used by the subject to command roll of the simulated plant. The hardware implementation is shown in the block diagram of Appendix B. Analog representation of the controlled plant dynamics is presented in Appendix C.

The experiment was conducted in a room provided by the Environmental Medicine Division of the Aerospace Medical Research Laboratory. The room contained no windows and the doors were blocked off during the experiment sessions to assure a non-disruptive physical environment. The analog computer generating the controlled plant dynamics and the PDP-11 digital computer were located in a separate room upstairs. Existing circuitry between patch panels and trunklines located in each of the rooms were used to provide connections to the display and control units. With the exception of the peripheral vision display circuits, the equipment was the same as that used in the previously mentioned experiment conducted by Junker and Replogle. Descriptions of the foveal and peripheral vision displays are given below.

Central (Foveal) Display. The foveal display was presented on a 12-1/2 in. by 12-1/2 in. square area of the Conrac television monitor. The inside-out display consisted of a 1-7/8 inch long rotating line whose center was superimposed upon a stationary horizontal line (see Fig. 3). A 1/8 inch perpindicular line at the center of the rotating line provided upright orientation. The angle between the rotating and stationary lines, ϕ_e, depicted the difference between the controlled plant roll angle and the forcing function roll angle. The foveal display was centered in azimuth a distance of 17-1/2 inches from the controller's eyes. Subjects' sitting heights were such that the foveal display was within 10 degrees of eye level of each subject.

Peripheral Display. The peripheral display was presented on two 21-inch televisions placed on opposite sides of the cockpit mock-up (Fig. 7). The televisions were positioned such that the vertical side of each of the sets' viewing screens most distant from the operator would be flush with a vertical plane passed through the face of the central display. The two television screens were located in the vertical such that the screens' vertical midpoints were within

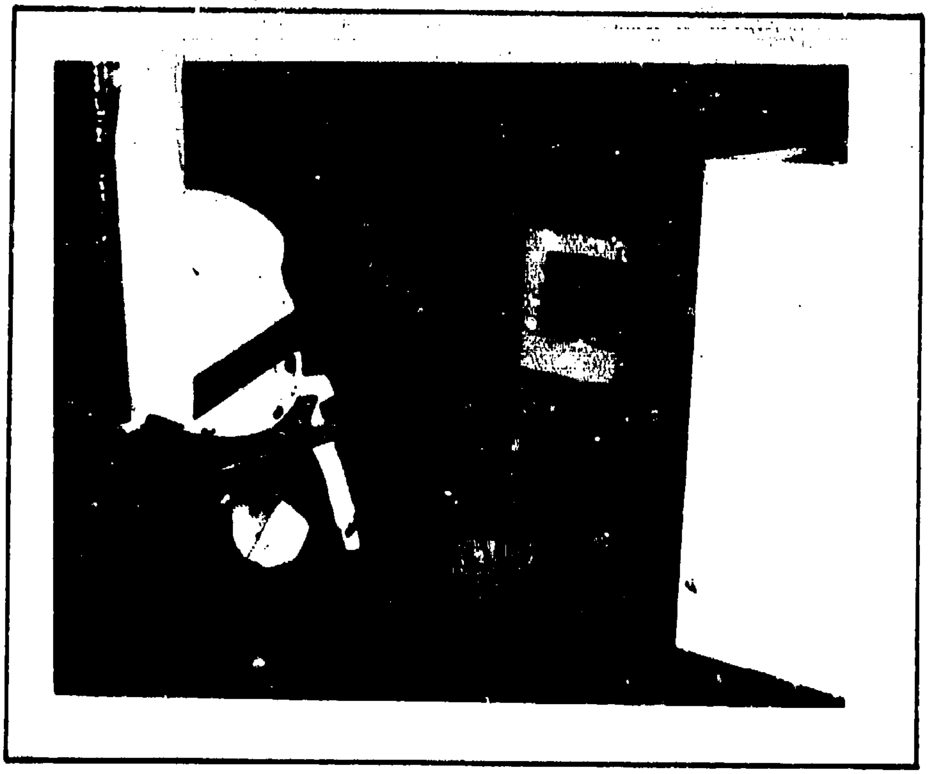

Figure 7. Seating Arrangement and Visual Displays

1-1/2 inches of subject eyelevel. The fixed position of the peripheral displays resulted in a horizontal peripheral viewing field from 40 degrees nasal to 90 degrees nasal. The displays subtended a vertical peripheral angle of approximately 40 degrees at the vertical side of each of the two viewing screens most distant from the operator.

The peripheral display presented plant roll rate information in the form of vertical movement of alternating black and white horizontal lines. The lines were adjusted to a width of 2-3/4 inches. The voltage representing plant roll rate was scaled and connected to a Wavetech signal generator whose output was connected to the televisions' sync circuits. Scaling was accomplished such that

$$V_p = 16.5\ \omega \tag{3}$$

Where V_p was the vertical velocity of the peripheral display in inches per second, 16.5 was the distance in inches between the center of the foveal display and the two peripheral displays, and ω was the instantaneous plant roll rate in radians per second. Linearity of V_p with respect to changing ω was verified. The peripheral circuitry was connected such that the displays of the two sets moved in opposite directions. With the circuitry and scaling as described above, motion about a longitudinal axis through the center of the Foveal display was simulated. A commanded ω resulted in a V_p equal in magnitude and direction to the linear velocity stationary objects located in the positions of the peripheral displays would appear to have, if the cockpit mock-up were to actually rotate. The use of moving alternating black and white lines to provide motion information was based upon experimental results of Ener. Ener successfully used this type of peripheral motion cue to display error rate while studying pilot performance during simulated glide-slope approaches (Ref 19: 22-23).

Plant roll rate was used as the peripheral motion cue in order to provide visually the same type of information available from roll motion effects. Subject performance could then be compared somewhat to the results obtained by Junker and Replogle in their study of roll-axis motion effects (Ref 18:810-822).

IV. Experimental Procedure

This chapter presents the experimental conditions and the procedures used to perform the experiment. Subject data is contained in Appendix D.

Conditions

Four experimental conditions were experienced by each subject. The compensatory tracking task was first presented with Plant No. 1 as the controlled plant and with a sum-of-sines input forcing function of 1.25 radians/sec bandwidth and 20 degree RMS amplitude. Each subject performed daily replications of the tracking task both with and without the peripheral display described in Chapter 3 until RMS error scores converged asymptotically, indicating that the subject had learned how to perform the task in a manner which was indicative of his best performance. The controlled plant was then changed to the more difficult Plant No. 2 and the input forcing function adjusted for a 0.5 radian/sec bandwidth and 40 degree RMS amplitude. Daily replications with and without the peripheral display were accomplished by each subject until, again, the RMS error scores indicated that the subjects had reached a sustained level of task proficiency. Thus, each of the subjects performed as many as 36 replications of the four different experimental conditions, the number of replications being dependent upon the task learning requirements of the subjects.

Subject Briefing

All subjects were briefed extensively prior to beginning the experiment. The briefing was in two parts: an explanation of the subjects' task followed by a separate discussion on how the peripheral display was to be utilized by the subjects. The subjects were divided into two groups of three for the first series of experimental runs with one group performing their runs in the morning of each day and the second group running in the afternoon. In addition, the morning subjects were to run initially without the peripheral display and the afternoon group were to make all of their first series of runs with the peripheral display. For this reason, the subjects were briefed separately by group. In order to standardize the briefings, printed instructions (contained in Appendix B) were prepared which described the subjects' task and the use of the peripheral display. The morning group was not briefed on the peripheral display until they were to begin experimental runs using the peripheral cues. In each case, the method of briefing was to have the subjects read the appropriate instruction sheet(s) after which the information and instructions were presented verbally. The initial briefings on the control task and use of the peripheral display are discussed in the following two paragraphs.

For the control task briefing, the subjects were given a printed sheet to read which described the task. After reading the information sheet, the instructions and explanations were repeated verbally. The subjects were told that they were to minimize the roll angle difference between their simulated aircraft and a simulated target aircraft which would be making random motions about the roll axis. The actual visual display of the task (Fig. 3) was shown the subjects at this time. The subjects were told to apply left and right pressure to the force stick in such a manner as to maintain the rotating line upright and as closely aligned as possible with the stationary horizontal dashed line. In this manner, it was explained, they would be minimizing the angular difference, with the two aircraft being perfectly aligned when the rotating line was superimposed upon the stationary line. Questions concerning the control task, foveal display, and control stick were answered after which it was emphasized to the subjects that it was extremely important that they strive to perform the control task as best they could at all times. The subjects were informed that each experimental run would last approximately three minutes and that their RMS error score would be displayed for information purposes after each run.

The same procedure was followed when briefing the subjects on the use of the peripheral display. After reading the peripheral display handout, the subjects were briefed on the contents. The vertical motion of the horizontal black and white grid lines presented on the two television screens was explained in detail. The briefing included the handout statement that the peripheral vision motion cues were provided to give the subject a sense of the rolling motions of the aircraft they would be "flying" about the roll axis. The subjects were told that the lines would move vertically in the direction stationary objects would appear to move if the cockpit were to actually rotate when force stick pressure was applied; e.g. for a right roll command, the grid lines of the display on the right would move upward and the grid lines on the left display would move downward. The subjects were instructed to not look directly at the peripheral display; instead, the subjects were to maintain eye contact with the central error display at all times. They were told to simply be aware of the type of motion information displayed on the TV screens and, with their peripheral vision, to use the motion cue information in any manner which seemed natural in assisting them in accomplishing the control task.

After answering questions, each initial briefing was concluded by allowing the subjects to perform the control task approximately 10 minutes. The peripheral displays were utilized when the briefings covered the use of the peripheral displays.

The three morning group subjects and one of the three afternoon group subjects had recently served as subjects for a compensatory roll axis tracking experiment designed to study motion effects on the human operator and which employed controlled plant dynamics similar to the plant dynamics used in this research effort. In the previous experiment, the same cockpit and foveal display were used and the cockpit motion was produced by the roll axis motion of the controlled plant. The earlier experiment, however, did not utilize any type of peripheral vision display.

Procedure

The conduct of the experimental runs utilizing Plant No. 1 was different from the runs utilizing Plant No. 2 controlled plant dynamics. The change in procedure was necessitated because two of the three afternoon group subjects were not available for the Plant No. 2 sessions. The four subjects used with the Plant No. 2 experimental runs were treated as a single group for analysis purposes and the sequence in which the Plant No. 2 experimental conditions were experienced by each subject were different from the sequence associated with the Plant No. 1 controlled plant dynamics. Experimental procedures are detailed below.

Plant No. 1 Procedures. Each subject experienced one session five days a week and each session consisted of taking four replicates of one experimental condition. The morning group subjects, who were all experienced with the non-peripheral condition due to their participation in the motion effects study, were run without the peripheral display first. The intent was to continue the daily sessions until the subjects' individual RMS error scores indicated that they had "learned" the tracking task. After learning occurred, the morning group repeated the procedure with the peripheral displays added for each run. The afternoon group followed the same procedure except that the two experimental conditions were reversed. The afternoon group first performed the tracking task with the peripheral displays; then, after the RMS scores indicated learning had occurred, the sessions were accomplished without the peripheral displays. A particular sequence was observed while accomplishing the individual replications during each session. Each subject in a group experienced two consecutive 165 sec replicates of the tracking task. After the third subject in a group accomplished his second run, the subjects completed the session by experiencing two additional replicates of the tracking task in the same subject sequence as before. The sequencing resulted in a rest period of approximately 15 minutes for each subject between his first two replicates and his last two replicates of each session. The subjects were provided their RMS error score after each run.

Each subject wore a flight helmet with intercom capability while performing the tracking task. The subject was permitted to track the target briefly prior to each scored run in order to adjust mentally and physically to the tracking task. The recorded run was commenced upon a verbal signal from the subject. The phase relationships of the input forcing function component sinusoids were programmed to differ (using a random number generator) for each replication and, hence, prevent learning of the input.

Lighting effects and external distractions were also considered when planning the experiment procedures. The subjects were required to sit in the laboratory room for ten minutes prior to beginning each session. The room was indirectly lighted by a 15 watt florescent desk lamp located 15 feet out of view of the subjects. During each experiment run, the cockpit was enclosed with a removable tarpaulin placed in front and on either side rearward to a point abeam the aft portion of the subject's seat. The tarpaulin was used to prevent subject distraction and to allow only an extremely low level of indirect lighting to illuminate the cockpit. The subjects were permitted to adjust the focus and brightness controls of the central error display. Subject adjustments of the brightness control resulted in an approximate error display luminance of 1 foot-lambert. The peripheral displays were adjusted to provide a sharp black and white contrast of the 2-3/4 inch grid lines at a brightness level that the subjects felt was satisfactory. The brightness level of the peripheral displays was not altered during the experiment. Luminance of the black grid lines was 0.25 foot-lamberts and luminance of the white grid lines was 6 foot-lamberts.

Plant No. 2 Procedures. After all desired data runs had been accomplished using Plant No. 1, the experiment conditions were changed by introducing the more difficult Plant No. 2 as the controlled plant dynamics. As previously mentioned, two of the three subjects in the Plant No. 1 afternoon group were not available for the remaining experiment runs. For this reason, the subjects were treated as one group and their results analyzed on an individual basis as well as a single group basis. Furthermore, the author decided to serve as a fifth subject. The author reasoned that his results would increase the sample size if careful analysis showed that his performance was not biased due to knowledge of the overall experiment effort and objectives.

The subjects performed their daily tracking sessions the same time of day as they previously had with Plant No. 1. The author performed his daily sessions with the one subject from the Plant No. 1 afternoon group. Each subject experienced one session five days a week and each session consisted of two sittings, with each sitting consisting of two runs. Each subject would perform, in sequence, one sitting; after the last subject performed his first sitting, the sequence was repeated. In order to insure that separate control strategies could be developed without biasing, each subject sitting consisted of one run with peripheral and one run without the peripheral display. Thus, for each daily session a subject would perform a total of four tracking runs, two of which used the peripheral display and two which did not.

Another change for the Plant No. 2 runs was that the subjects' sequence of sittings was rotated on a daily basis. For example: For the three subjects who ran in the morning, Subject A would run first one day, third the next, second the following day, and would run first again on the fourth day. All other experiment procedures were as described for Plant No. 1.

Fusion Speed Investigation

An attempt was made to determine the peripheral display grid fusion speed for each subject. The subject was asked to look at the center display while the controlled plant was slowly "rotated" at increasing angular velocities. When the subject stated that he could no longer detect separate grid lines with his peripheral vision, the plant angular velocity was recorded. Each subject performed four replicates of the fusion speed test. The fusion speed tests were not considered adequate to determine exact values. The results were used to obtain an approximate plant angular rotation corresponding to the fusion speed to assist in frequency domain analysis of subject performance. Certain observations concerning fusion speed are presented in Chapter 6.

Data Recording

Daily RMS error scores and complete time histories of pre-determined experimental runs were recorded. The digital computer program calculated the RMS error score after each experiment run. The score was displayed on the subject's central display and a remote central display monitor. The RMS error scores were plotted daily in order to evaluate subject and group performance.

Once the RMS error scores indicated that the subjects of an experimental group had "learned" the tracking task for a given experimental condition, time histories were recorded on a computer disk for use in analyzing subject control strategy. Time histories from the last session using Plant

No. 1 dynamics and time histories of the last two sessions employing Plant No. 2 dynamics were recorded and consisted of input forcing function, error, stick, and controlled plant output signals. The number of subject runs recorded, and total group data runs for each experimental condition, are summarized in Table I.

Table I

Number of Recorded Runs for Each Experimental Condition

Experimental Condition	Recorded Runs Per Subject	Total Recorded Runs Per Group
Plant No. 1 Without Peripheral Display (Morning Group)	4	12
Plant No. 1 With Peripheral Display (Morning Group)	4	12
Plant No. 1 Without Peripheral Display (Afternoon Group)	4	12
Plant No. 1 With Peripheral Display (Afternoon Group)	4	12
Plant No. 2 Without Peripheral Display	4	20
Plant No. 2 With Peripheral Display	4	20

V. Data Reduction and Analysis

This chapter presents methods used to convert recorded time histories into meaningful data for analysis purposes. Assumptions made concerning statistical treatment of the reduced data are discussed.

Data Reduction

The sampled data recorded on computer disks was converted to desired performance measures using a frequency analysis digital computer program provided by Mr. Andrew Junker of the Environmental Medicine Division of the Aerospace Medical Research Laboratory. The analysis program employed the Fast Fourier Transform (FFT) for computational purposes. General properties and computational aspects of this highly efficient method for computing the discrete Fourier transform of discrete data samples can be found in the literature (Ref 20:45-55). The program was used to compute both correlated and remnant components of the input, error, stick (subject), and plant power signals and the transfer characteristics (describing functions) for the subject, controlled plant, and subject-plant combination. The plant describing function was used to provide a check on the programmed dynamics. Salient aspects of the methodology are presented below.

As discussed in Chapter 2, remnant power is spread in a continuous fashion throughout the response bandwidth. For a twelve-component sum-of-sines input, however, correlated power exists only at the 12 nominal input frequencies. For each recorded experiment run, the remnant power was calculated at the FFT frequencies over a frequency band encompassing 0.125 octaves on either side of, but not including, each nominal frequency. Correlated power at the nominal frequency was then computed by subtracting the averaged remnant power from the power measured at the nominal frequency. Correlated power thus obtained, of the error, stick and plant signals was then used to estimate the describing functions. As an example, the subject describing function was calculated as

$$Y_s(\omega_i) = C(\omega_i)/E(\omega_i) \tag{4}$$

where $Y_s(\omega_i)$ is the transfer characteristic of the subject at the ω_i nominal input frequency, and $C(\omega_i)$ and $E(\omega_i)$ are the corresponding discrete Fourier coefficients of the control and error signals. The calculation of $Y_s(\omega_i)$ yielded a complex number which was converted to a magnitude (in db) and phase angle.

Certain limitations existed in the data reduction and warrant comment. Experiment run length was not only an important consideration concerning subject performance but also had ramifications upon sampled data calculations. This was due to the fact that the interval between successive FFT frequencies is equal to the value of the base frequency

$$\omega_0 = 2\pi/T \tag{5}$$

where ω_0 is in rad/sec and T is the measurement interval or run length. The 0.25 octave remnant averaging "window" about low nominal input frequencies, therefore, contains significantly fewer FFT intervals than the averaging windows about the higher nominal frequencies. The measurement length for the subject tracking task in this experiment resulted in a base frequency of $\omega_0 = 0.038$ rad/ sec. The 0.25 octave averaging window about the five lowest nominal input frequencies contained only 2 measurement intervals. For a perfectly flat remnant spectrum, Levison states that a -3 db estimation error can be expected for calculations based upon 2 samples, although one cannot apply this correction with any degree of certainty in a given measurement situation (Ref 10:A-3). Calculations from remnant averaging are the values presented in this report.

One other limitation with data reduction was that the amount of correlated power existing at the nominal input frequencies could not be precisely determined. As described above, correlated power at each nominal frequency was obtained by subtracting average remnant power from total power at the nominal frequency. The surrounding remnant power was compared with the total power at each nominal input frequency. If the difference was less than 6 db, the estimate of correlated power (and therefore correlated subject response) was considered unreliable. Data obtained from the unreliable estimates was not considered in the determination of averaged correlated power spectra and describing functions. Unreliable data points are omitted from the presentation of results in Chapter 6. For this reason, certain power spectra and describing function plots have fewer than the twelve nominal frequency data points. Data points most affected were those of the lowest three nominal frequencies.

Data Analysis

Analysis of averaged group data for each experimental condition is presented in this report. This method of presentation was decided upon after investigating individual subject performances for notable differences with the control strategies implied by the averaged group data. The number of individual subject replicates included in the group averages is summarized in Table I located at the end of Chapter 4 - with one exception. Two Plant No. 2 time histories of one subject were accidentally erased from the disk prior to accomplishing any analysis. Eighteen replicates, therefore, were used to compute Plant No. 2 group averages.

Group data presented in Chapter 6 includes group means and plus-or-minus one standard deviation values. Previous compensatory tracking experiments similar to the one used in this study (but without peripheral cues provided) indicate that the data will be normally distributed (Ref 7:110). Data analyzed in this experiment is assumed to be normally distributed in order to facilitate comparison of group means.

A small sample t-test, as explained by Chapanis (Ref 20:122-126), was applied to determine statistical significance of apparent differences in group mean data. For example: If a difference in Plant No. 2 group mean values of the subject describing function (Y_s) was observed at a particular frequency, the small sample t-test was applied to Y_s data at the frequency of interest. Values from the eighteen replicates of each of the two experimental conditions were used as population samples. Statistical comparisons of group data permitted meaningful analysis of the manner in which the peripheral display influenced task performance.

VI. Results

This chapter presents the results of the experiment data reduction and analysis. Emphasis is upon determining if the peripheral motion cues improved subject performance of the compensatory tracking task and, when performance was improved, determining how the peripheral cues were used. Overall subject performance is presented first with RMS error scores of the tracking task as the performance metric. Results of statistical analysis of the RMS error scores are presented as an indicator of peripheral cue effects upon task performance. Analysis of subject control strategy follows and is performed in the frequency domain. Plant No. 1 results are treated first. Frequency domain analysis centers upon investigation of the subject and subject-controlled plant describing functions (Y_s and Y_sY_c, respectively) and the correlated and remnant power spectra of the error signal.

Before results can be properly interpreted it is necessary to discuss one problem encountered with the Plant No. 1 simulated dynamics. A circuit malfunction required that the Plant No. 1 dynamics be reprogrammed on the analog computer. This problem occurred (and was corrected the same day) after the morning group without-peripheral data was recorded, but prior to recording any other time histories. Group mean plant describing functions computed from time histories indicated that the original controlled plant gain was approximately 2 db less than the reprogrammed plant gain. In addition, the plant pole near the origin was identified as being at approximately s = 0.88 for the original plant as opposed to s = 1.0 for the reprogrammed dynamics. The last RMS error scores recorded with the original Plant No. 1 dynamics (see Fig. 8) were Day 1 for the morning group with the peripheral display and Day 7 for the afternoon group, also with the peripheral display present.

The author's data from the Plant No. 2 tracking sessions is included in the results presented in this chapter. As discussed in Chapter 4, the author's data was to be included in order to increase the sample size only if careful analysis showed that his performance was not biased due to knowledge of the overall experiment effort and objectives. The author's RMS error scores and frequency domain data reflected the same general trends and values when compared with the other subjects' data.

RMS Tracking Error

The daily tracking scores for each subject in an experiment group were combined to yield group means and standard deviations. The results for Plant No. 1 and Plant No. 2 are presented in Fig. 8 and 9, respectively. The means (indicated by circles) and standard deviations are plotted by day for each of the two experimental conditions encountered with each plant.

Discussion

The Plant No. 1 RMS error scores plotted in Fig. 8 are

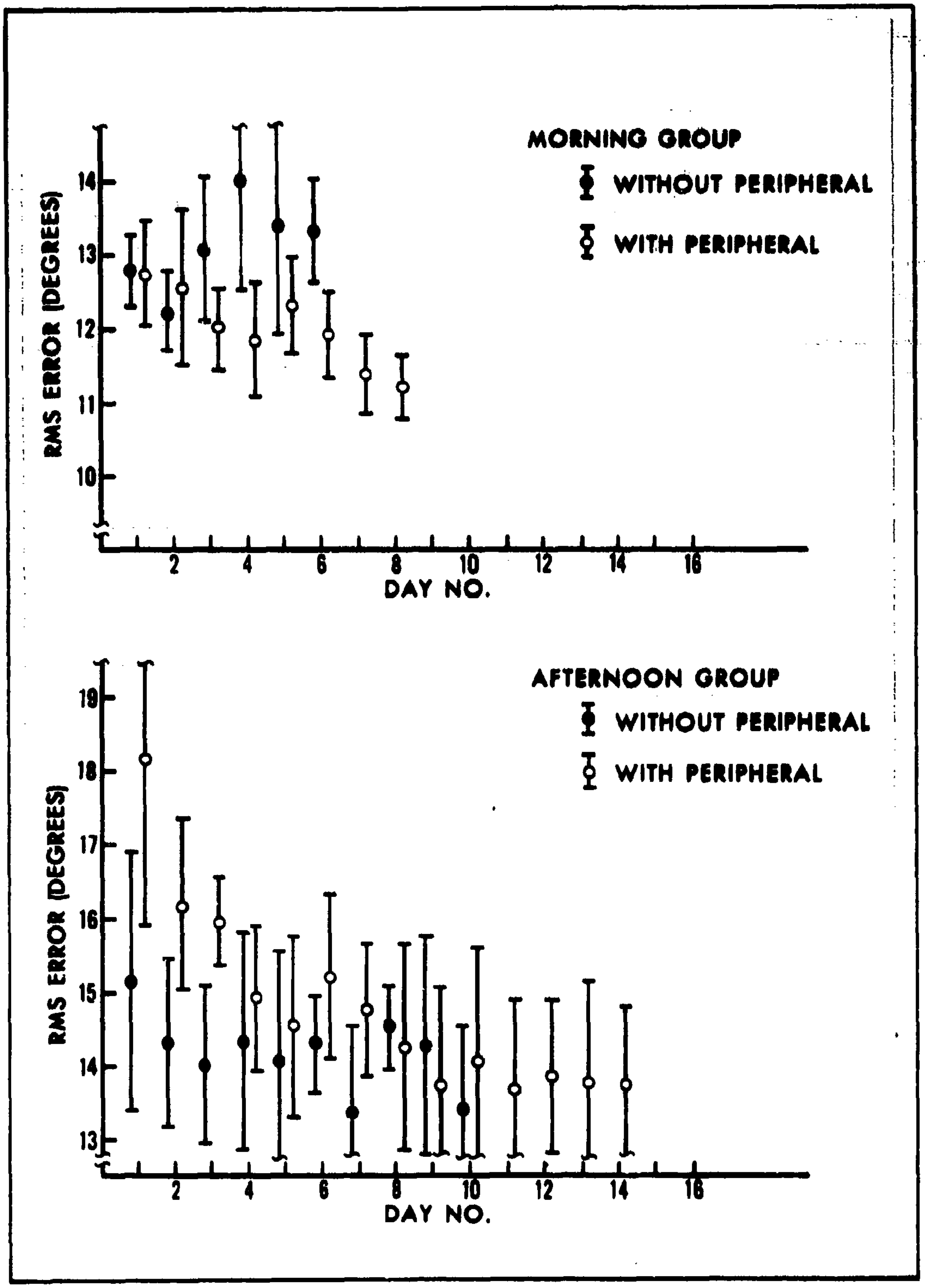

Figure 8. RMS Error Scores for Plant No. 1

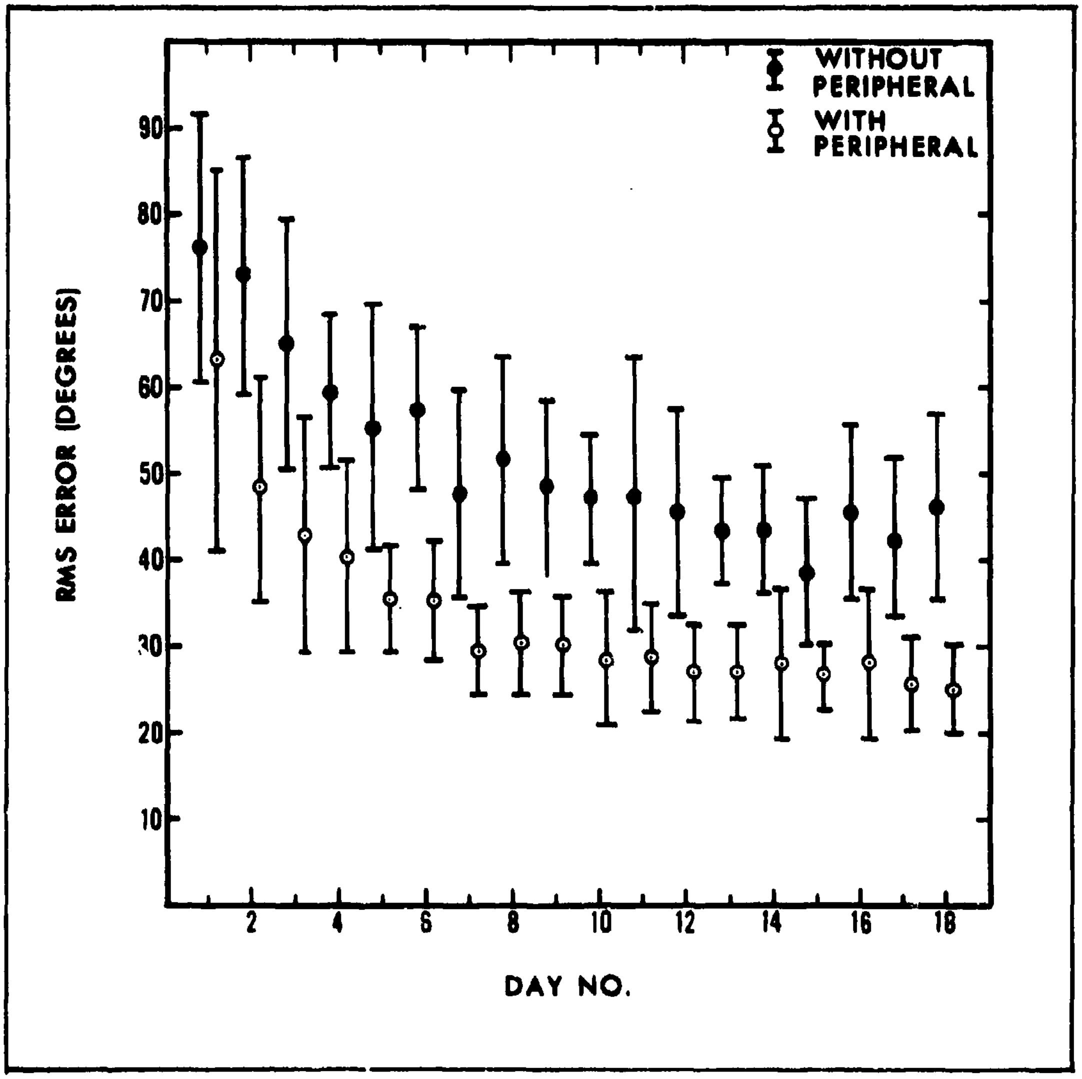

Figure 9. RMS Error Scores for Plant No. 2

for a forcing function bandwidth of 1.25 rad/sec. Plant No. 2 RMS error scores are depicted in Fig. 9 and are for a forcing function bandwidth 0.5 rad/sec. Tracking tasks for a given experimental condition were terminated when the mean RMS error scores for a group and for all subjects within a group indicated task learning had been achieved. Asymptotic convergence of mean score plots was used as the indicator that subjects had reached their level of task proficiency for the time allotted for the experiment. Because of the programming problem, the influence of peripheral information upon the morning Plant No. 1 group could not be accurately assessed. The afternoon group data, however, indicates that the peripheral vision motion cues probably did not significantly improve the afternoon group's performance. A small-sample t-test was applied to determine if the peripheral cues did, in fact, influence the tracking scores. For plant No. 1 afternoon group runs, subject scores recorded the last data day for each of the experimental conditions were used as the two population samples for significance testing. RMS scores recorded the last two days were used for testing peripheral influence on Plant No. 2 runs.

Results of the t-test of Plant No. 2 population samples indicated that the peripheral vision motion cues significantly influenced subject performance. The test revealed that the difference between sample groups was significant at less than the 0.001 level. No significant difference was noted for the Plant No. 1 afternoon group (<0.6 level).

Certain subjective comments concerning Plant No. 1 performance are in order before proceeding with the frequency domain data results and analysis. Two of the three members of the morning group and all three members of the afternoon group stated that the peripheral vision motion cues did not aid them in performing the control task. The RMS error scores of the one subject who disagreed reflected the same variable trends as the other two subjects in his morning group - the with-peripheral scores were generally between 1 and 2 degrees lower for each subject. The discrepancy between the morning group subject scores and evaluations is attributed primarily to the unplanned difference in controlled plant dynamics. Boredom was a possible secondary influence upon morning group performance. All three morning subjects had recently served as subjects for a compensatory tracking experiment employing similar plant dynamics as Plant No. 1, but without the peripheral display. The same cockpit arrangement was used in the earlier experiment. Because of time considerations and group performance, morning group runs without the peripheral display were discontinued after the sixth day. An increase in subject enthusiasm was noted when the experimental condition was changed.

Frequency Domain Analysis

Frequency domain data and analysis of the tracking task results are presented separately for the two controlled plants with Plant No. 1 results treated first.

In order to determine if the subject's tracking performance improvement with the peripheral display present was due, at least in part, to the correlated portion of his response, attention is first directed to the group mean subject-controlled plant describing functions (Y_sY_c) and then to the group mean subject describing functions (Y_s). This sequence appears most logical for any apparent differences in Y_sY_c should be reflected in the Y_s describing function since Y_c is known and is invariant. The associated error signal power spectra (Φ_{ee}) are then examined to possibly assist in clarifying describing function observations and to compare remnant data. All data plots depict group mean values in circles and plus-or-minus one standard deviation. Stick signal power spectra are not presented in the body of this report but are included in Appendix F for the interested reader. Differences in group Y_s describing functions are statistically tested for significance.

Plant No. 1 Performance. With the Plant No. 1 dynamics differing as discussed previously, it is not possible to properly investigate the describing functions of interest. Fig. 10 and Fig. 12 presents the Y_sY_c group-averaged describing functions for the experimental condition in which peripheral cues were not available; Fig. 11 and Fig. 13 depict Y_sY_c with peripheral vision motion cues present. Plus-or-minus one standard deviation bands are included in all the figures.

Of immediate interest are the two Y_sY_c describing functions of the morning group (Figs. 10 and 11) since the controlled plant dynamics were slightly different. According

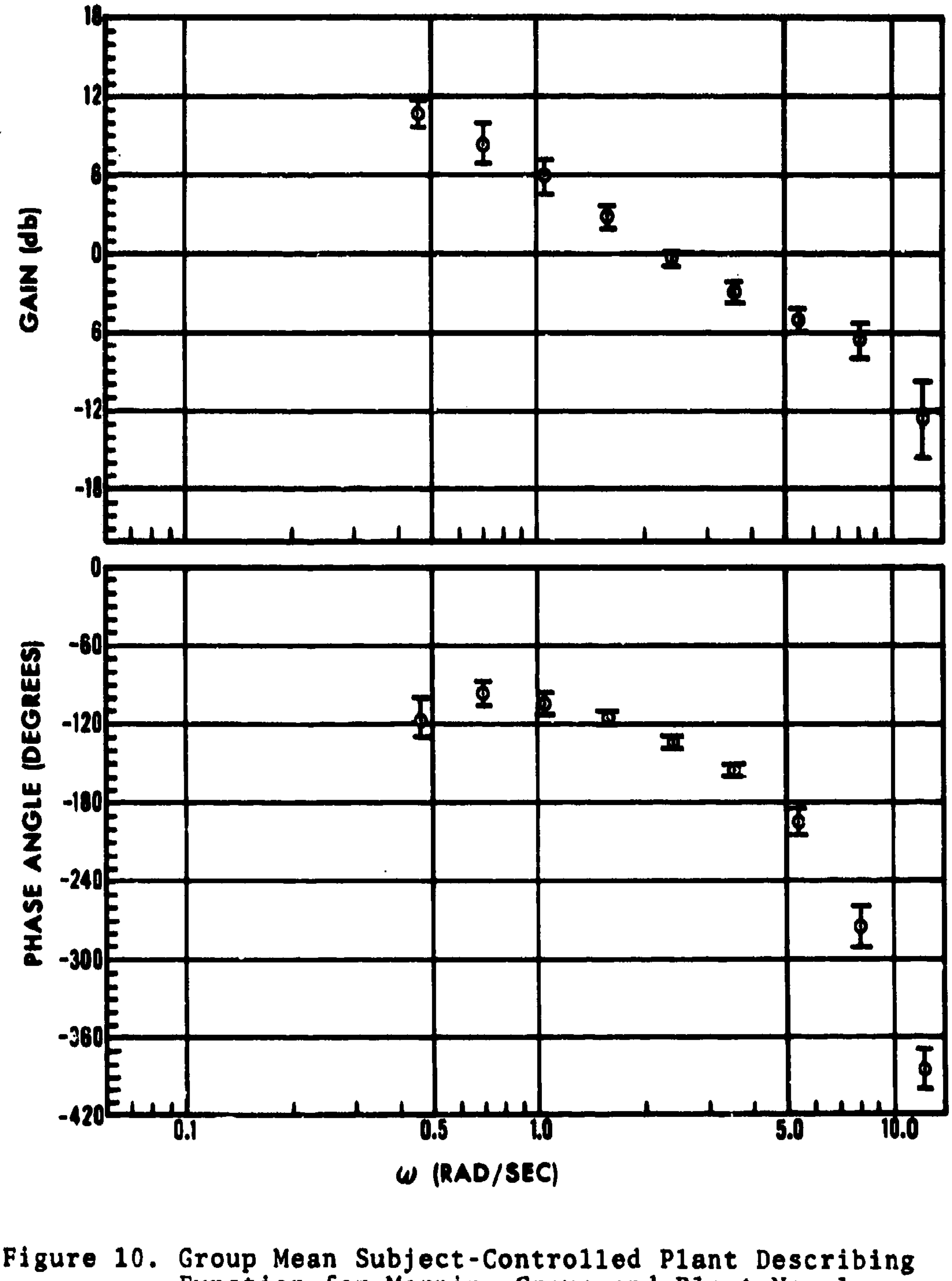

Figure 10. Group Mean Subject-Controlled Plant Describing Function for Morning Group and Plant No. 1 - Without Peripheral Display

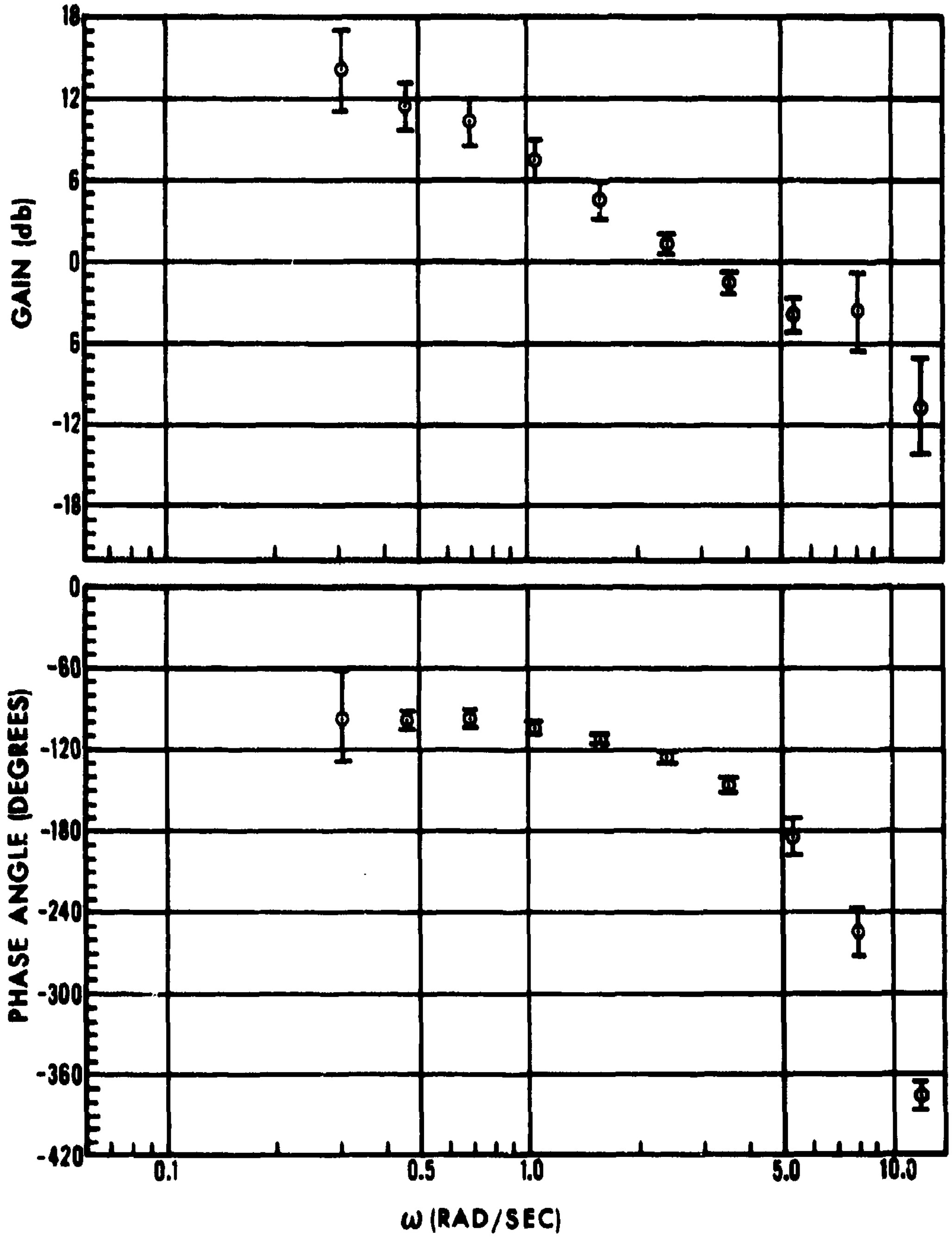

Figure 11. Group Mean Subject-Controlled Plant Describing Function for Morning Group and Plant No. 1 - Peripheral Display Present

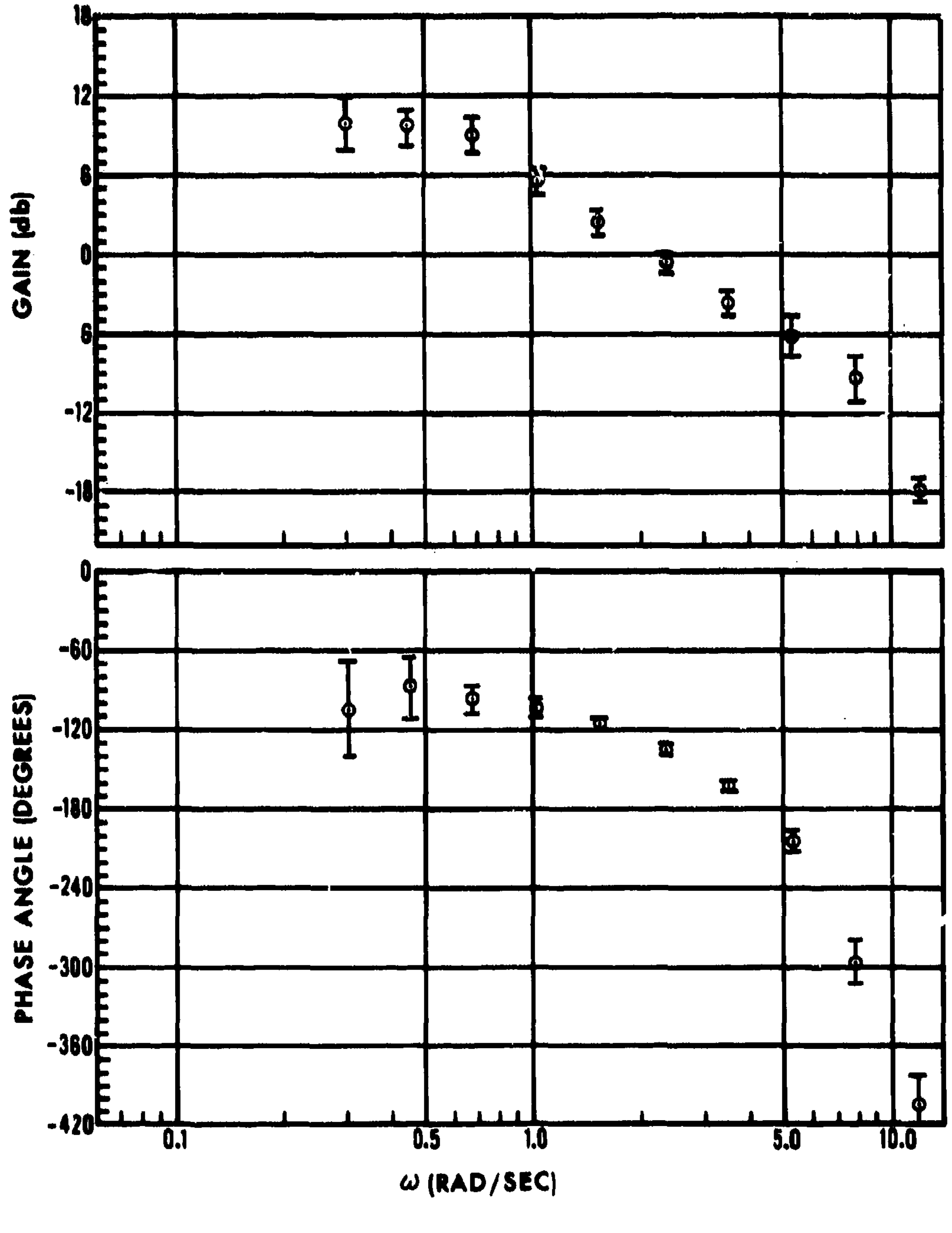

Figure 12. Group Mean Subject-Controlled Plant Describing Function for Afternoon Group and Plant No. 1 - Without Peripheral Display

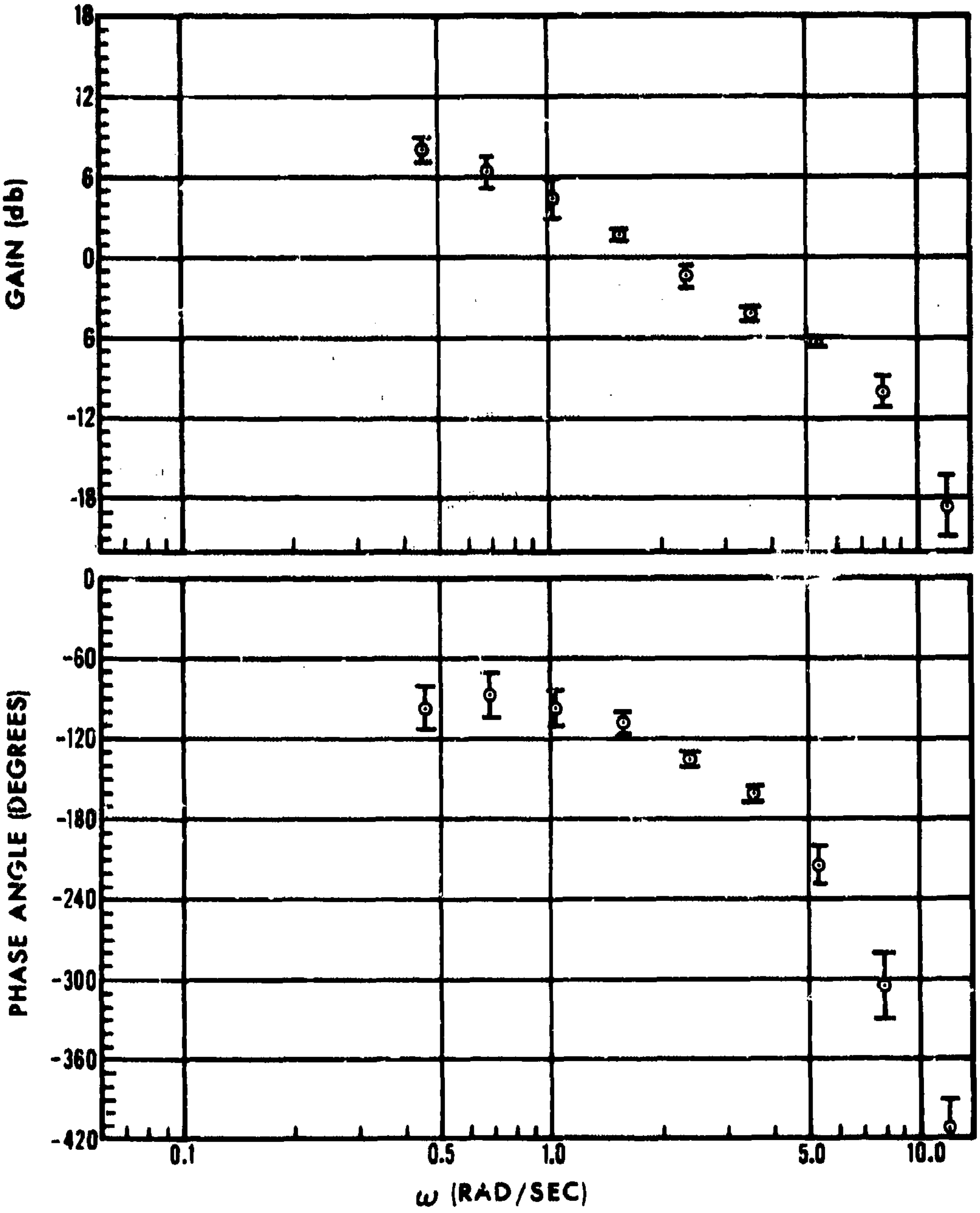

Figure 13. Group Mean Subject-Controlled Plant Describing Function for Afternoon Group and Plant No. 1 - Peripheral Display Present

to McRuer et al., for a given controlled plant, system crossover is invariant with controlled element gain. This is because the human controller will offset element gain by adjusting his gain accordingly (Ref 7:19). If the poles of the two plants were the same, the gain crossover frequency, ω_c, of the two Y_sY_c describing functions should be the same; in fact, they are not (ω_c = 2.85 rad/sec with the peripheral display vs ω_c = 2.2 rad/sec without the display). If the magnitude curve of Y_sY_c without peripheral is increased by 2 db, however, the two Y_sY_c magnitude plots become strikingly similar. This implies that the morning group subjects controlled both plants with the same gain but exhibited slightly different control adjustments at the low and high frequencies of the measurement range which resulted in the two Y_sY_c magnitude curves being similar in shape. A further observation is that if 3 db of gain is added to each of the afternoon group Y_sY_c describing functions, all four describing function magnitude curves would be similar below ω = 5 rad/sec. The Y_sY_c describing function magnitude plots imply that the morning group subjects were controlling with an average of 3 db greater gain than the afternoon subjects.

With the gain differences reconciled, Y_c influences on each of the Y_sY_c describing functions become more apparent. Phase angles indicated a low frequency contribution from each of the Y_s describing functions. The afternoon Y_sY_c describing functions reflect Y_s contributions with a resulting phase margin of approximately 52° in each case. The same general low frequency trends are indicated for the morning group Y_s describing functions. The high frequency data indicates a bigger lead contribution by the morning Y_s describing functions. A 3 db greater gain for the morning group Y_s describing functions could explain the 45° phase margin for the case where the morning group's controlled plant was the same as the afternoon group's controlled plant. The high frequency slopes and phase angles indicate the morning group subjects were providing more lead compensation at frequencies above $\omega = 5$ rad/sec. Y_sY_c data, based on above interpretations indicates the following Y_s characteristics:

a. Morning group mean Y_s describing function gains were approximately 3 db greater than the afternoon group Y_s gains.

b. Lead adjustments varied slightly at the lower frequencies and higher frequencies for morning group Y_s describing functions.

c. Afternoon group Y_s describing functions were the same for both Plant No. 1 experimental conditions.

If the Y_s describing functions reflect these characteristics and can be statistically verified, the correlated portion of subject control responses can be analyzed and compared.

Group average Y_s describing functions and plus-or-minus one standard deviation bands are shown in Figs. 14-17. The Y_s data agrees with the Y_s characteristics implied by the Y_sY_c describing functions. Afternoon group Y_s data points which differed the greatest in value for the two experimental conditions were at $\omega = 0.460$ and $\omega = 1.035$ rad/sec. The difference was not significant at the 0.5 level at $\omega = 0.460$

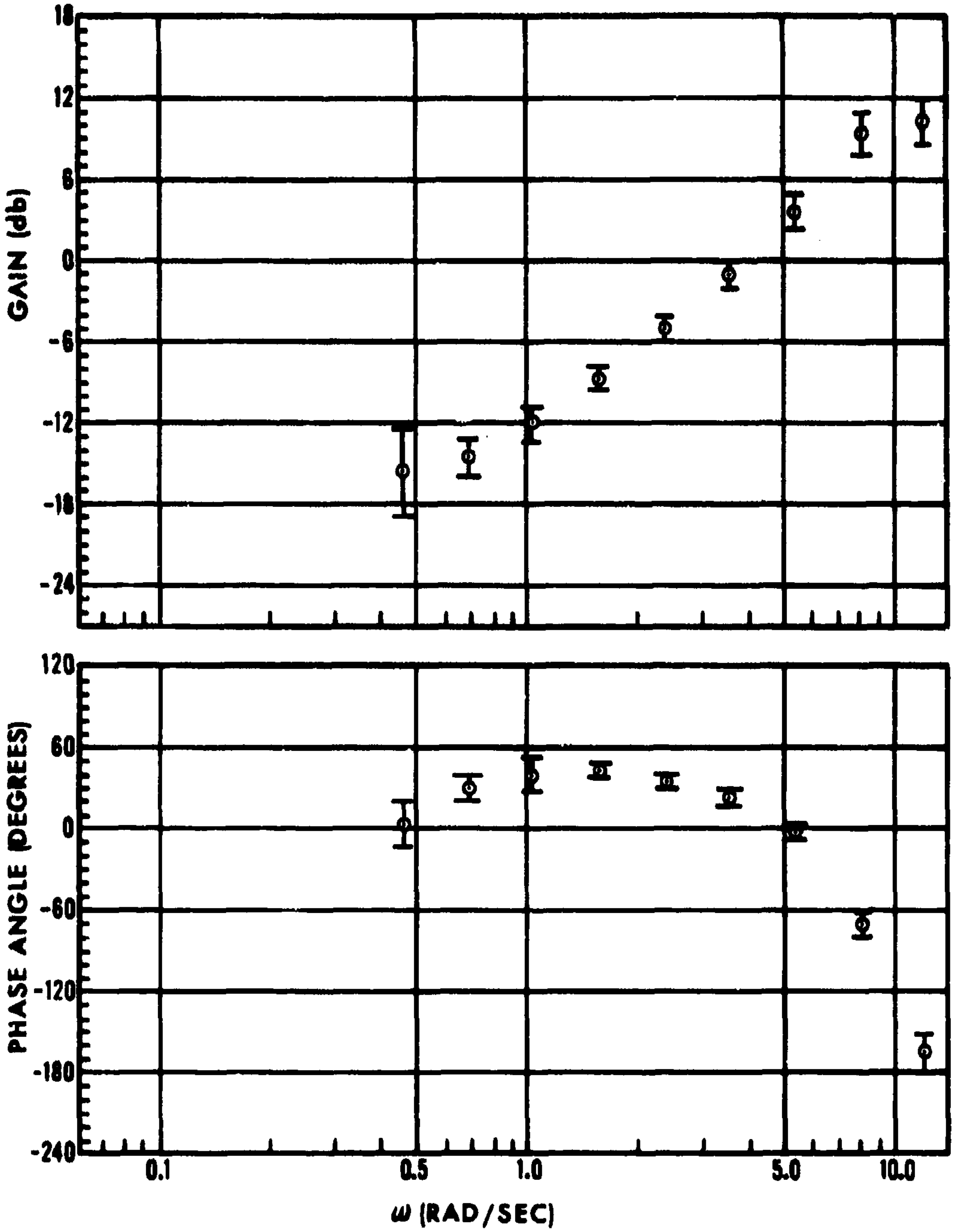

Figure 14. Morning Group Mean Subject Describing Function - Without Peripheral Display

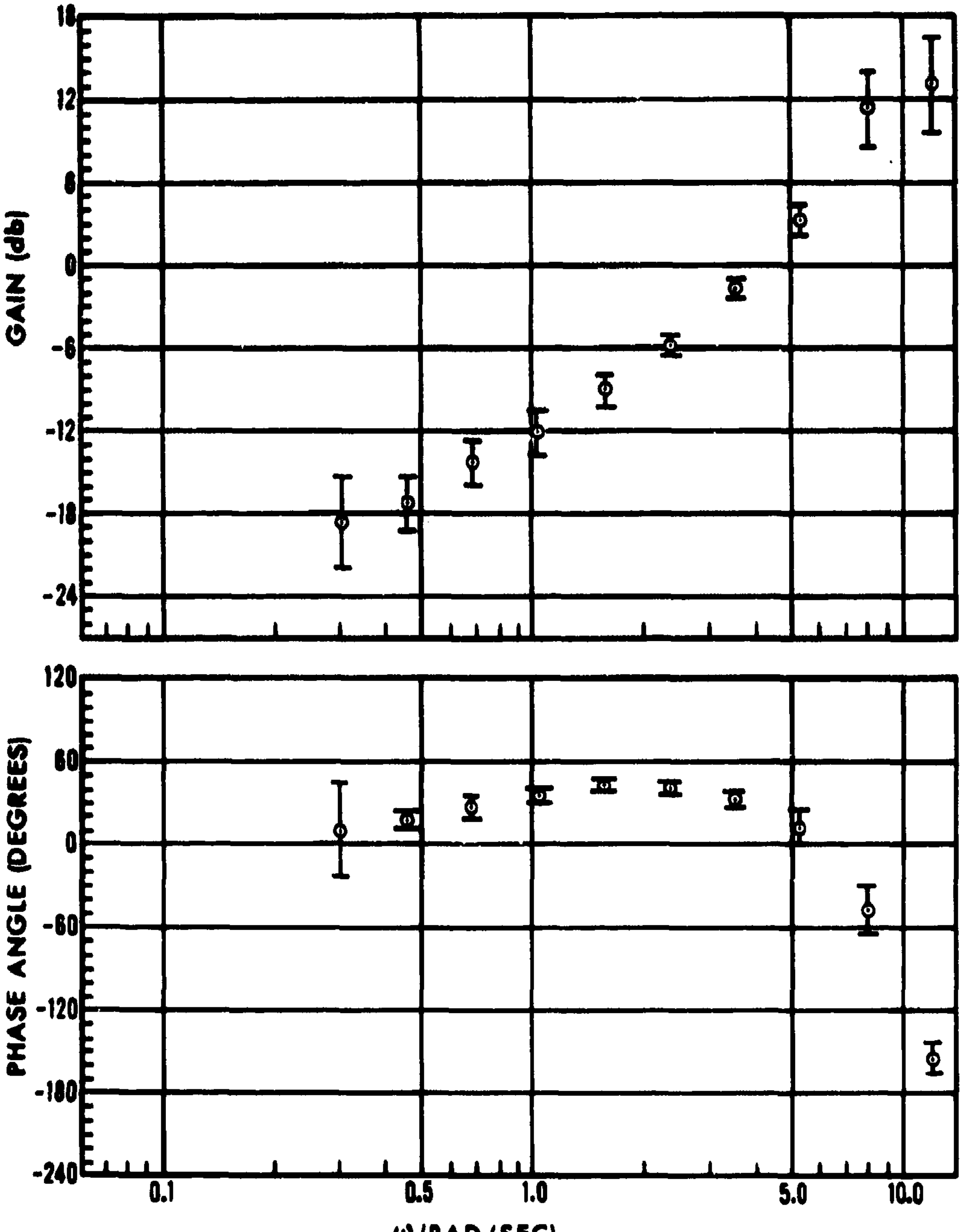

Figure 15. Morning Group Mean Subject Describing Function - Peripheral Display Present

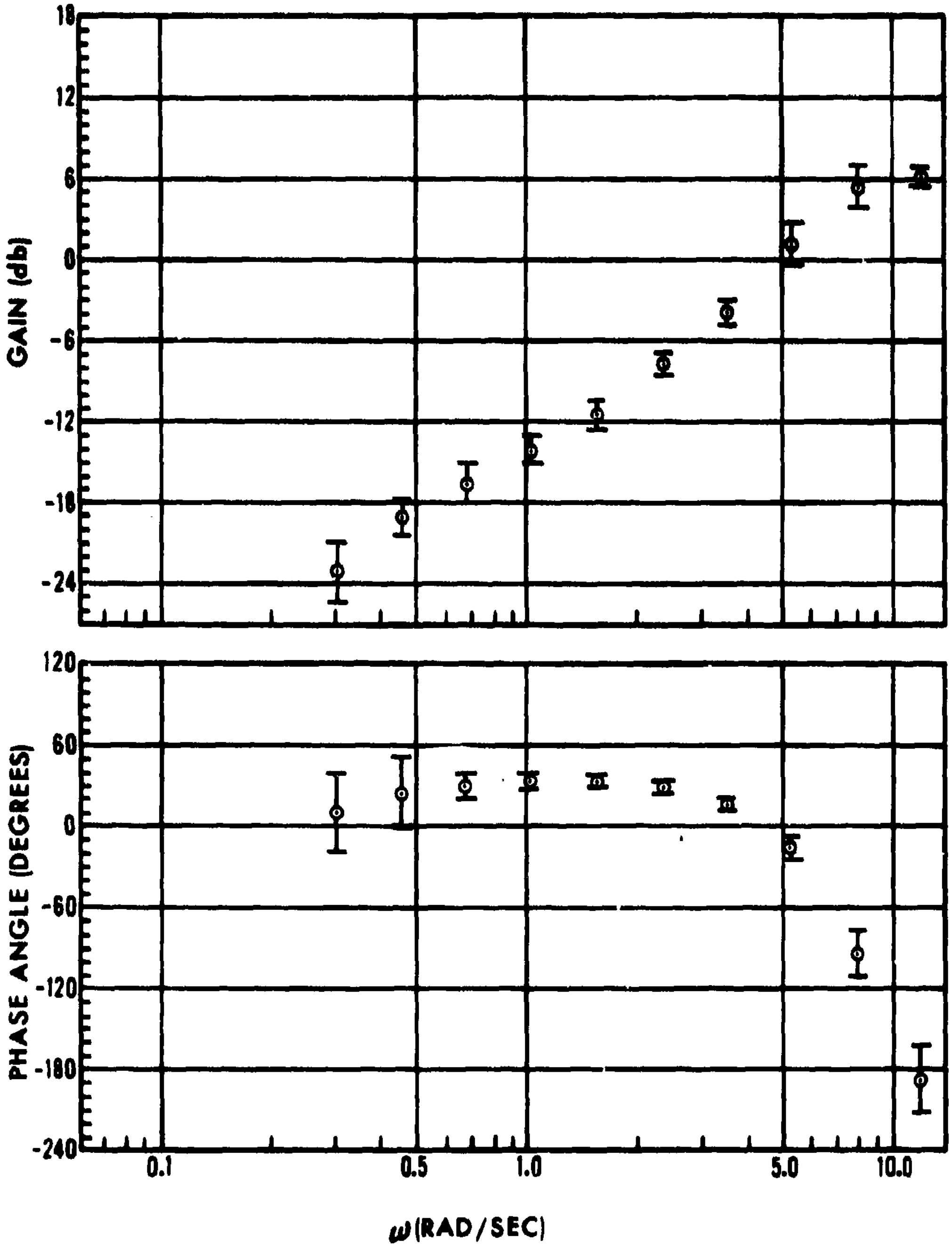

Figure 16. Afternoon Group Mean Subject Describing Function - Without Peripheral Display

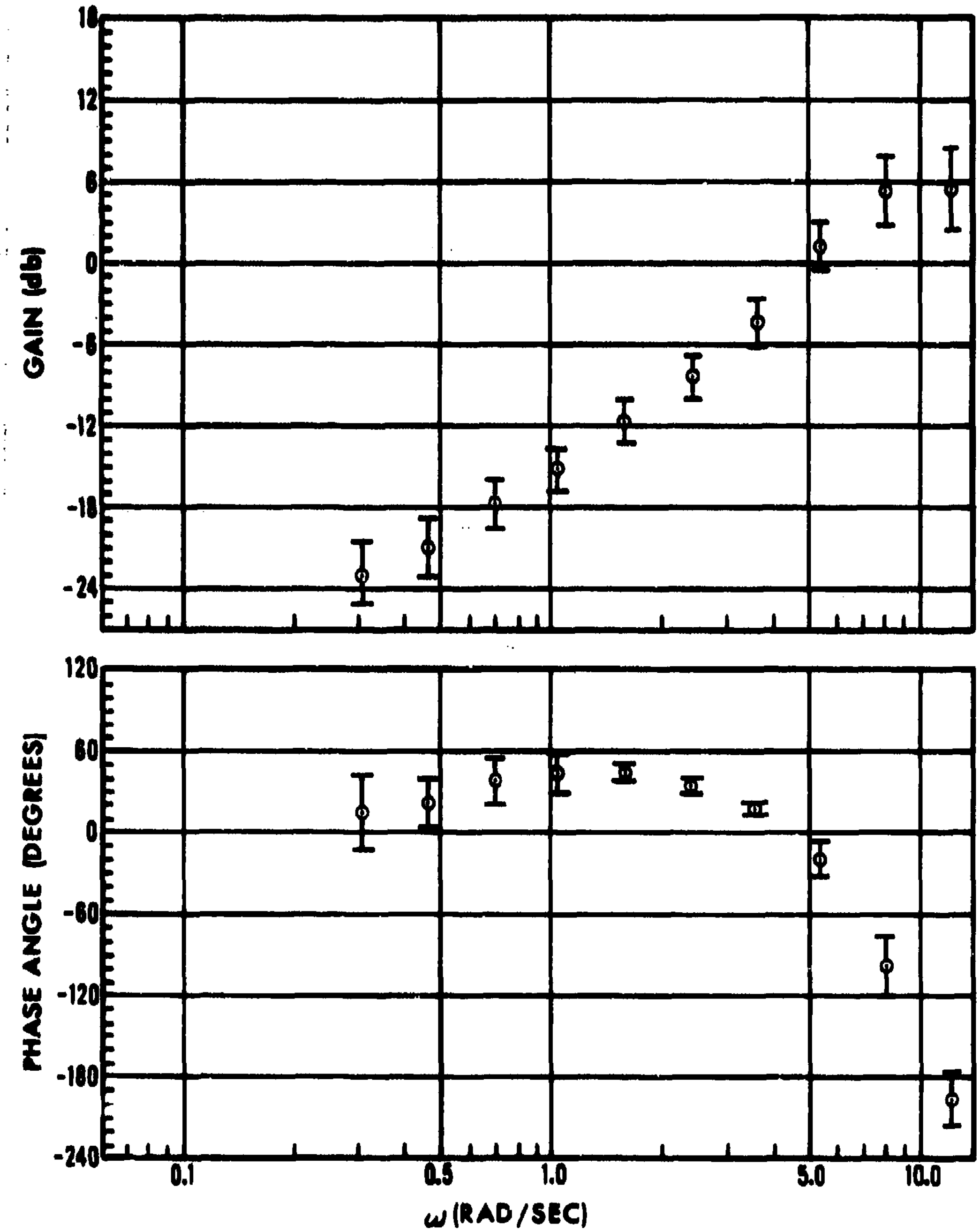

Figure 17. Afternoon Group Mean Subject Describing Function - Peripheral Display Present

rad/sec; at $\omega = 1.035$, the difference was not significant at the 0.1 level. Both afternoon group Y_s describing functions exhibit similar lag-lead adjustment characteristics. First order lead was applied over the measurement range through the crossover frequency but the accompanying phase angles indicate lag/time delay effects of similar magnitude below the measurement range. Additional lead was applied at frequencies beyond crossover prior to the well known high frequency neuromuscular lag effects appearing between $\omega = 5$ and $\omega = 10$ rad/sec.

The morning group Y_s describing functions indicate a similar type of control response. The measurement range does not permit precise evaluation of low frequency response. The morning group Y_s for the case where the peripheral cues were present approximates the afternoon group low frequency Y_s responses. The low frequency phase points vary slightly for the two morning group Y_s describing functions but were not tested for significance since the two controlled plants were slightly different. The same high frequency break point and phase droop are noted but are not as pronounced as with the afternoon group Y_s describing functions. The magnitude portion of the Y_s describing functions confirm that the morning group average Y_s gain was 3 db greater than that of the afternoon group Y_s.

Plant No. 1 group error power spectra averages with plus-or-minus one standard deviation bands are presented in Figs. 18-21. Included on the figures are the average per-

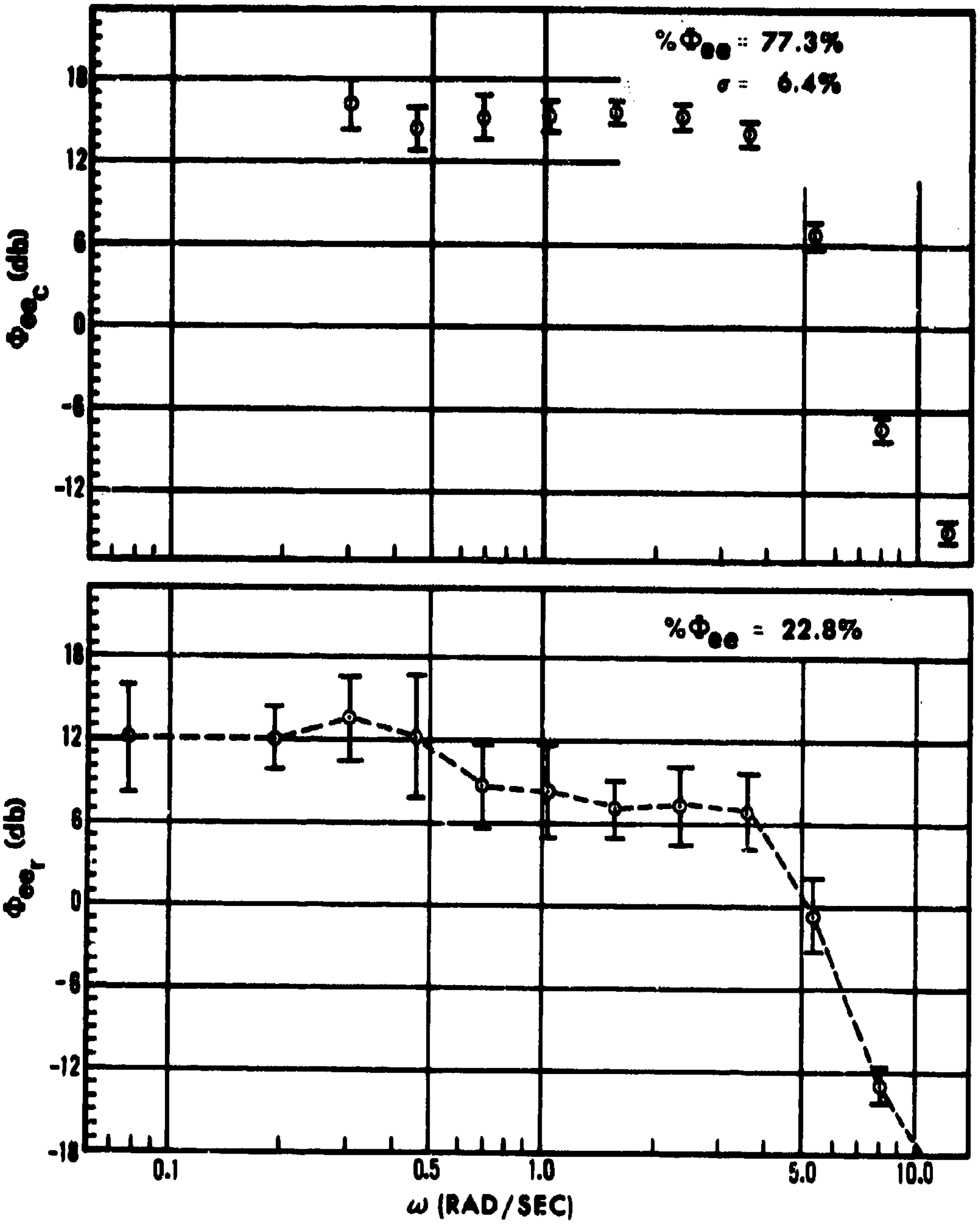

Figure 18. Averaged Morning Group Error Power Spectra - Without Peripheral Display

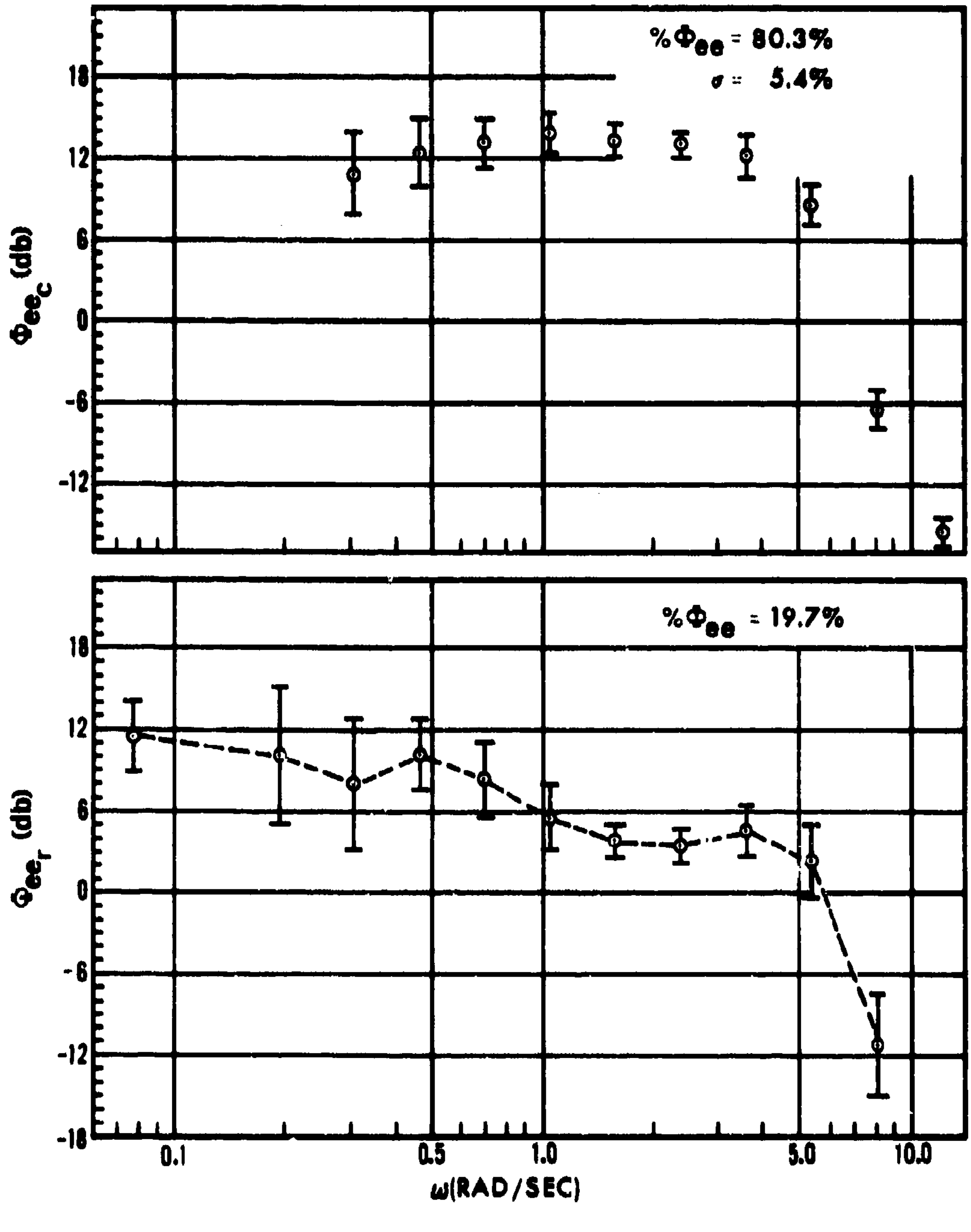

Figure 19. Averaged Morning Group Error Power Spectra - Peripheral Display Present

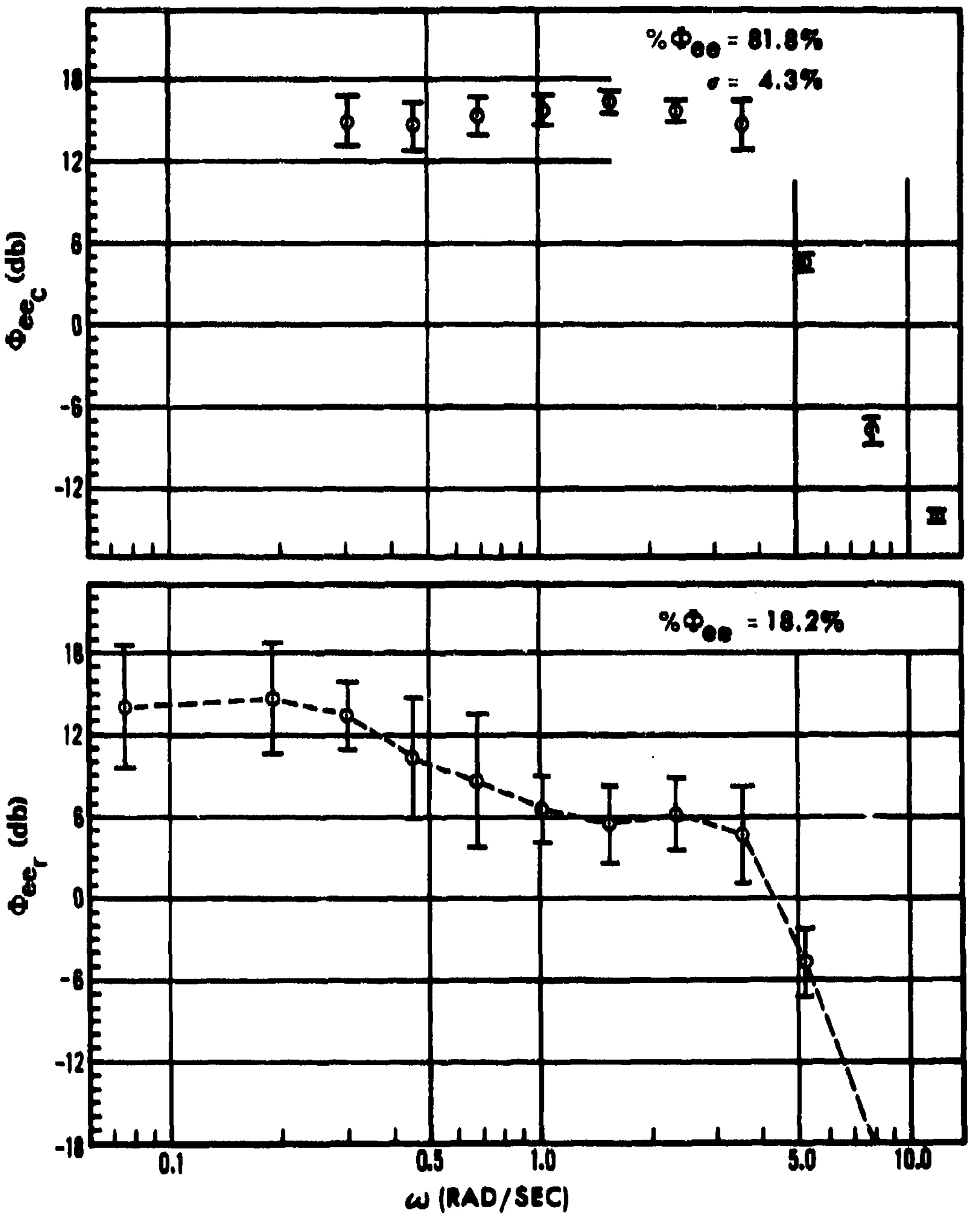

Figure 20. Averaged Afternoon Group Error Power Spectra - Without Peripheral Display

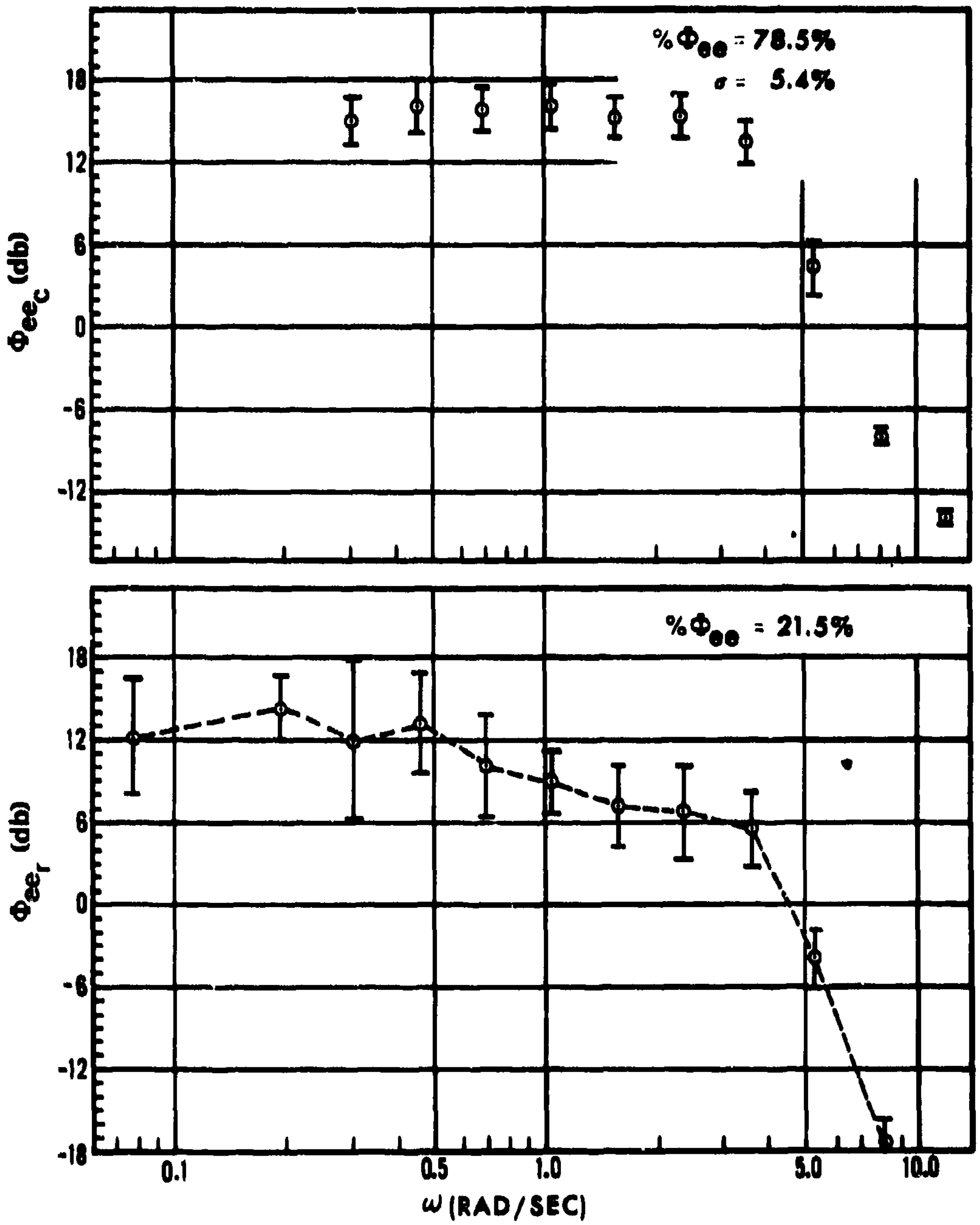

Figure 21. Averaged Afternoon Group Error Power Spectra - Peripheral Display Present

centage of total error power, and one standard deviation, calculated for correlated and remnant error contributions. In all four cases, the remnant error power was less than 25 percent of total error power. Errors introduced when attempting to separate the correlated and remnant portion of the error signal dictate that only gross magnitudes and signal characteristics be compared for any peripheral display effects on subject performance.

Correlated error power magnitudes were relatively constant at nominal input frequencies below and slightly beyond system crossover frequency. The correlated signals fell off sharply at nominal frequencies above $\omega = 4$ rad/sec where input signal power was minimal. The two afternoon group error power spectra reflect no significantly different characteristics. The flat portion of the spectra exhibit magnitudes of 14-16 db. The morning group error spectra, for the case where controlled plant dynamics were the same as the afternoon group, exhibits similar characteristics at nominal frequencies below $\omega = 4$ rad/sec. Magnitudes are less, however, and vary between 11 db and 14 db. The magnitude difference between morning and afternoon groups at $\omega = 2.378$, the nominal frequency nearest frequency crossover, is significant at less than the .001 level. Signal magnitude characteristics are similar at the higher nominal input frequencies.

The four continuous remnant power spectra were similar in waveform shape with the greatest values of remnant power occurring at the lower frequencies of the measurement band.

In each case, a lower magnitude plateau is evident for a frequency band that includes the system crossover frequency. The magnitudes are approximately 2-3 db less for the morning group case where controlled plant dynamics were the same as for the afternoon group performances. High frequency signal roll-off is the same as that noted for the correlated error signal.

Analysis of Plant No. 1 Performance. In order to minimize tracking error, the subject was required to adapt his control such that the bandwidth of frequency response of the combined subject-controlled plant forward control loop was extended beyond the frequency bandwidth of the controlled plant. This requirement is apparent when comapring the controlled plant Bode plot with the forcing function power spectrum of Fig. 4. For each experimental condition, subject lead equilization resulted in a Y_sY_c describing function of approximately -20 db/decade amplitude slope at system gain crossover - a design objective for any closed loop control system. Y_sY_c system crossover frequency and phase margin were approximately the same for both afternoon group describing functions. System crossover frequency was higher and the phase margin lower for the morning group Y_sY_c when the reprogrammed Plant No. 1 dynamics were employed.

The Y_sY_c and Y_s describing functions did not indicate any conclusive significant differences in subject control strategy due to peripheral display effects. Afternoon subjects, for each experimental condition, generated first order lead at frequencies below $\omega = 1$ rad/ sec. Associated phase angles indicated similar sensory processing time delays. The morning subjects demonstrated the same equilization characteristics but applied a 3 db greater gain than the afternoon subjects. The high frequence phase droop is slightly less pronounced for the morning group Y_s and is attributed to the additional lead generated by the morning group subjects at the higher frequencies prior to neuromuscular lag effects.

The better RMS error scores attained by the morning group controlling the reprogrammed dynamics are attributed to the correlated response of the subjects. The higher crossover frequency and 45 degree phase margin characterize a slightly more responsive closed loop control system. Error power spectra appear to reflect an improved correlated response. In the vicinity of system gain crossover, lower correlated and remnant error values are evident for the morning group. Effects of the peripheral display on the morning group cannot be properly evaluated however, since the controlled plant dynamics were different for the two morning group experimental conditions.

Plant No. 2 Performance. Subject-controlled plant describing functions with Plant No. 2 as the controlled element are presented in Figs. 22 and 23. Group means are indicated with circles and are accompanied with plus-or-minus one standard deviation bands. The Y_sY_c describing functions differ in amplitude slope and phase angle at the lower fre-

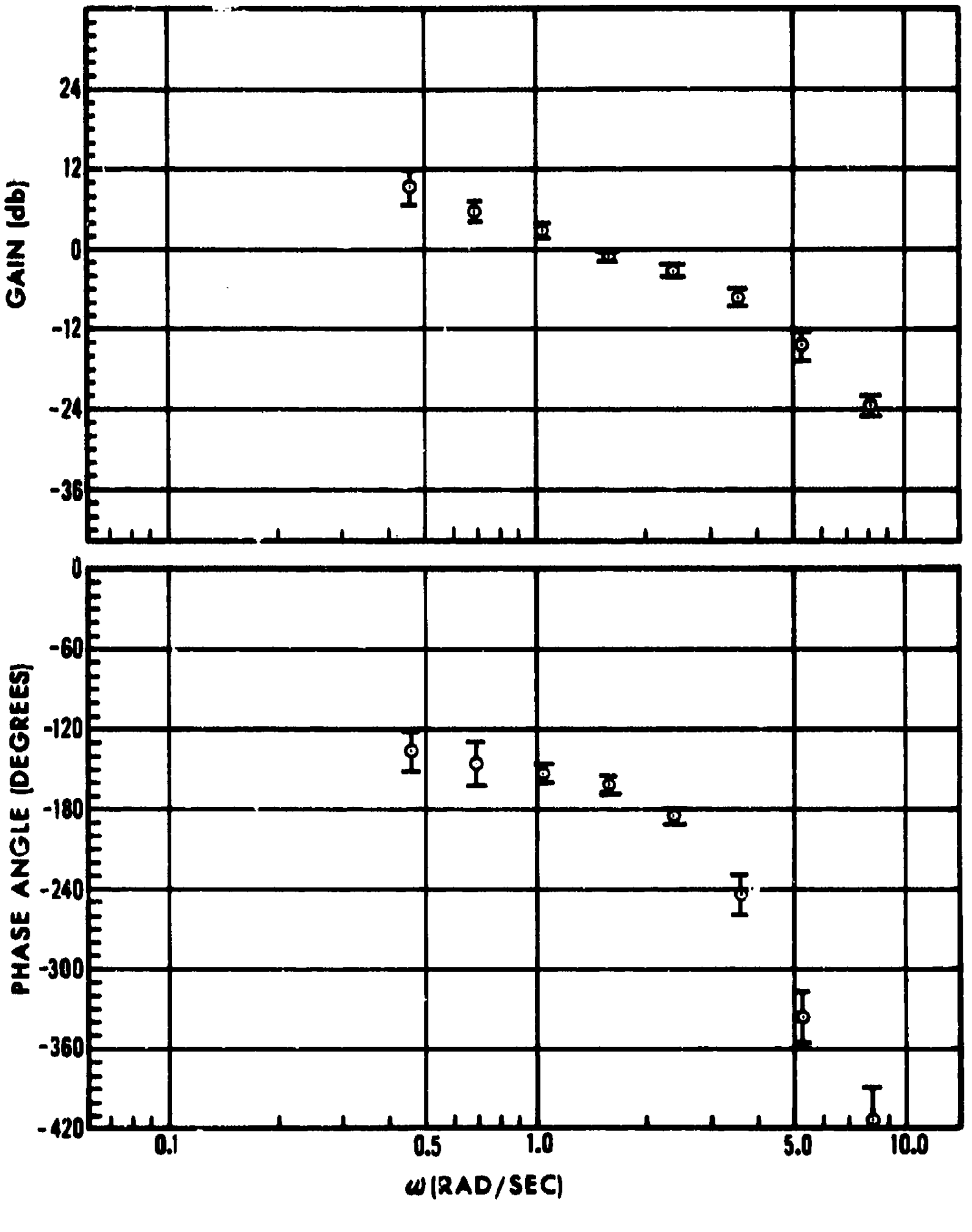

Figure 22. Group Mean Subject-Controlled Plant Describing Function with Plant No. 2 - Without Peripheral Display

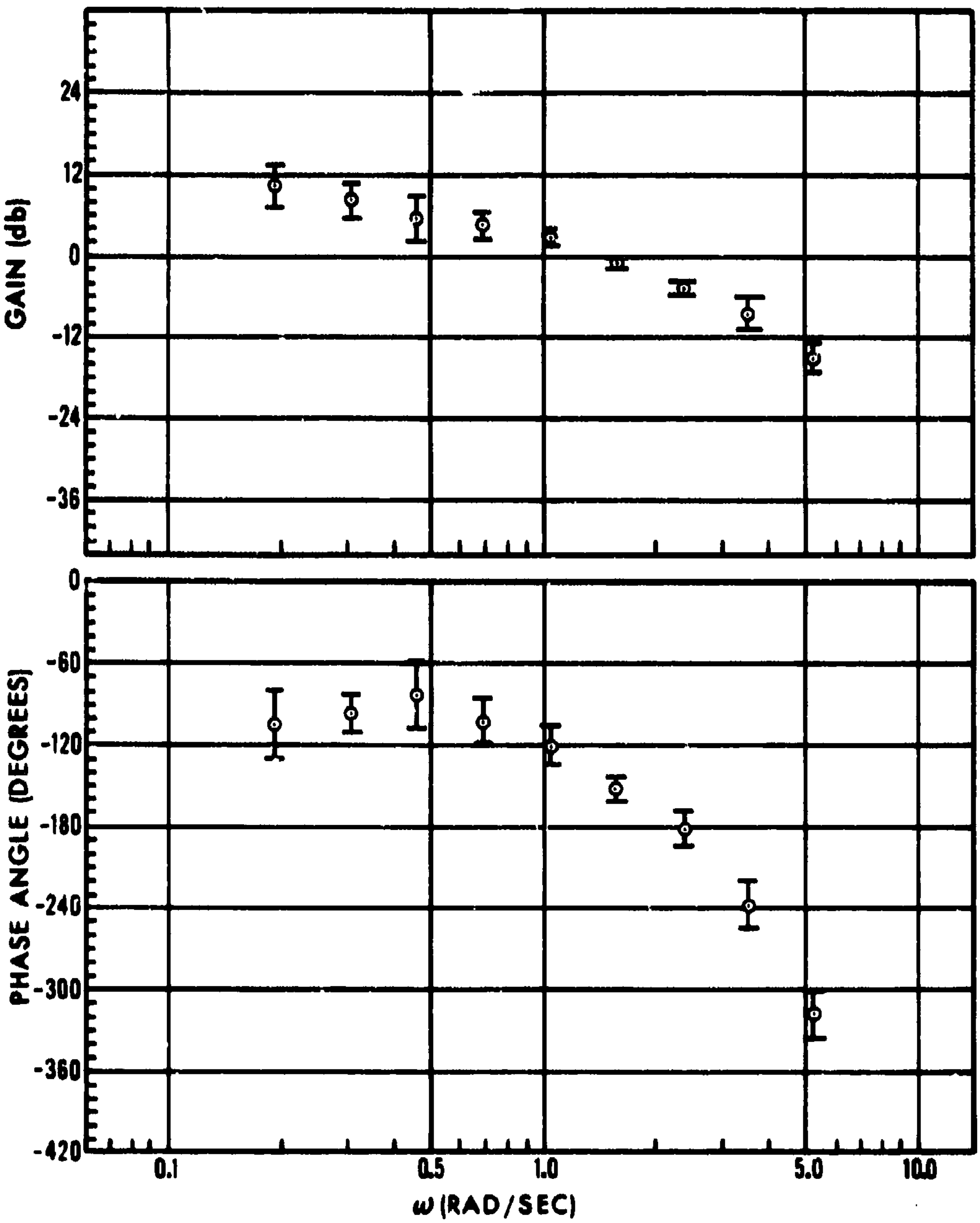

Figure 23. Group Mean Subject-Controlled Plant Describing Function with Plant No. 2 - Peripheral Display Present

quencies but are strikingly similar at the higher nominal input frequencies. System gain crossover occurs at $\omega = 1.4$ rad/sec with an amplitude slope of -20 db/decade for each of the two experimental conditions. Phase margins differ by about 16 degrees, however, with the condition where the peripheral display was present resulting in a larger phase margin ($\Phi_M = 38$ degrees with the peripheral display present vs $\Phi_M = 22$ degrees without the display). The two Y_sY_c data each approximate -20 db/decade slopes between $\omega = 1.0$ and $\omega = 3.6$ rad/sec and -40 db/decade slopes above $\omega = 3.6$ rad/sec. The phase angles, in each case, fall off sharply at the higher nominal frequencies, exceeding expected phase angle values associated with a -40 db/decade magnitude slope. At frequencies below crossover, magnitude slope and phase angle values indicate the presence of more low frequency lead when the peripheral display was present. With the Y_sY_c differences identified, it is possible to investigate the Y_s describing functions with the purpose of identifying the peripheral display influence upon subject correlated control response.

Group averaged subject describing functions, Y_s, are shown in Figs. 24 and 25. The Y_s data reflects subject control adjustments indicated in the Y_sY_c describing functions. The Y_s describing functions indicate that considerably more low frequency lead was generated with the peripheral display present. The phase angle differences at measurement frequencies ≤ 1.572 rad/sec were significant at less than the .001 level. Both Y_s describing functions reflect a 40 db/decade

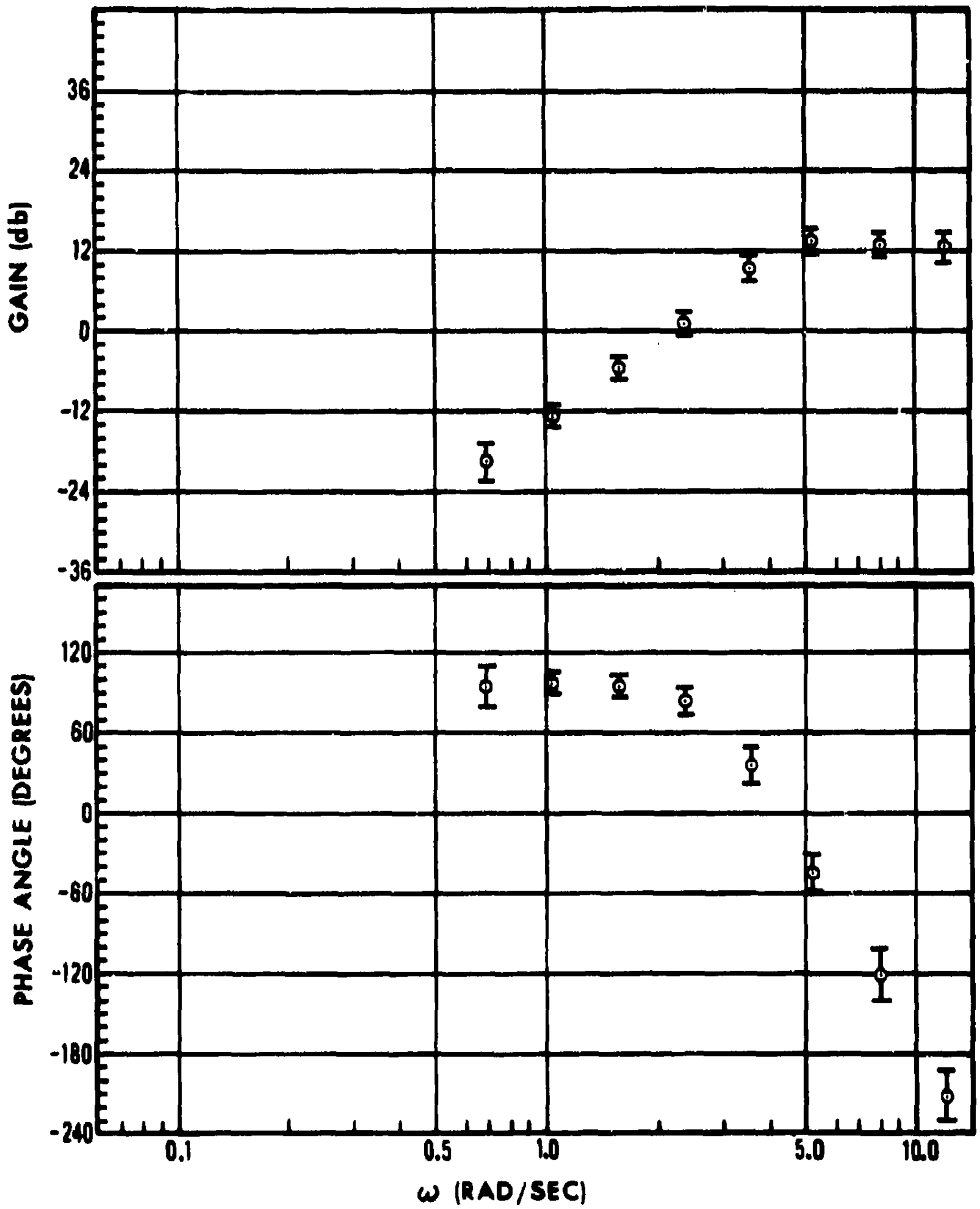

Figure 24. Group Mean Subject Describing Function, Plant No. 2 the Controlled Plant - Without Periphal Display

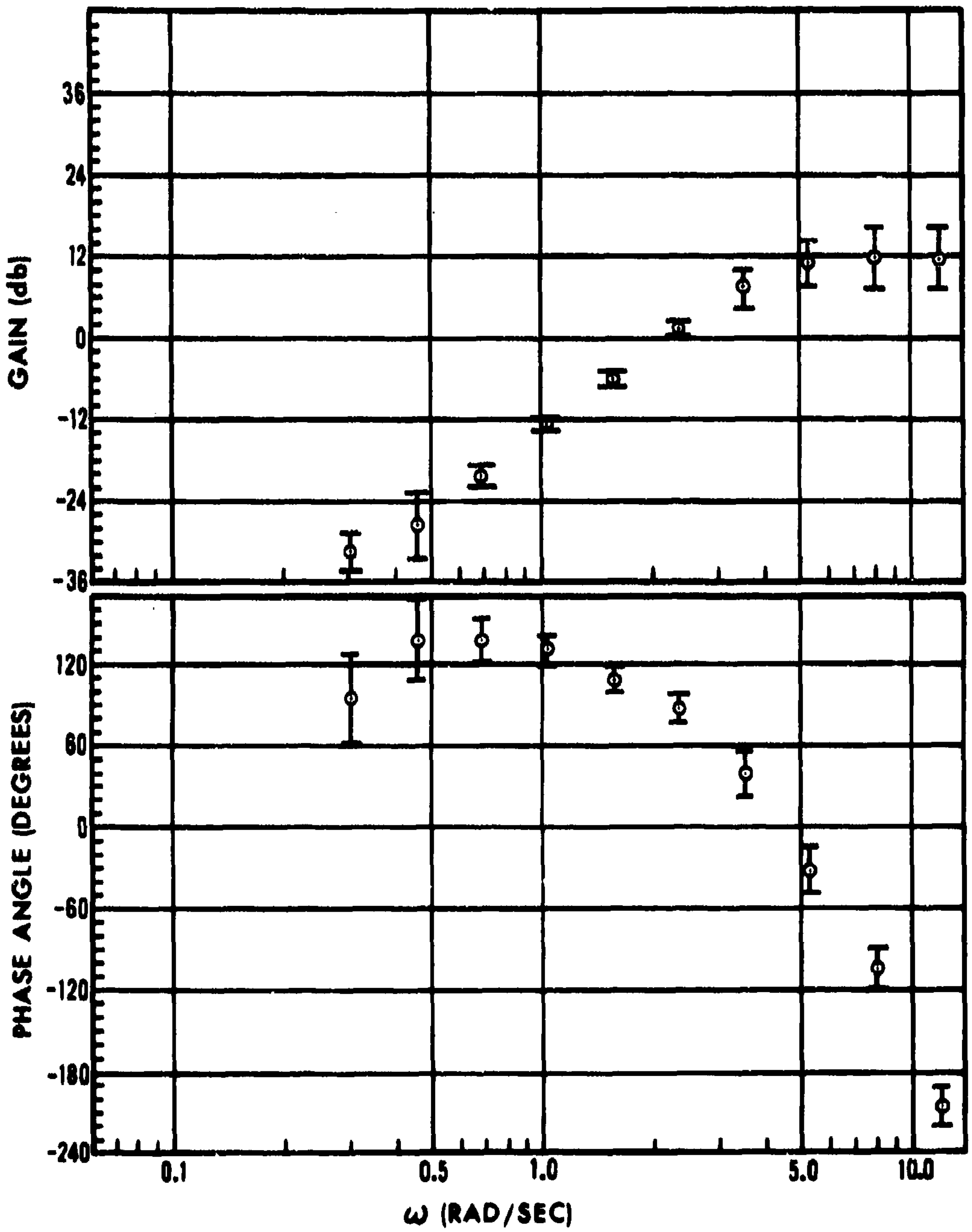

Figure 25. Group Mean Subject Describing Function, Plant No. 2 the Controll?d Plant - Peripheral Display Present

slope at the nominal frequencies about ω_c. High frequency neuromuscular lag effects are pronounced at nominal frequencies above $\omega = 5$ rad/sec with no difference in the effects noted for the two experimental conditions.

Error power spectra are shown in Figs. 26 and 27. The signal waveforms present the same general characteristics but differ in magnitude. Annotations on the figures reveal the significantly higher precentage of correlated error present when the peripheral display was available. Error correlated power is significantly less at the two nominal frequencies about ω_c. Both remnant spectra are relatively flat through ω_c and roll off sharply at higher frequencies similar to the correlated power high frequency decrease. Remnant power with the peripheral display present is consistently 4 to 6 db less at frequencies below gain crossover.

Analysis of Plant No. 2 Performance. The free integrater (1/s) in the controlled plant dynamics required the subject to provide derivative (lead) information in order to maintain control of the marginally stable plant. Plant rate (derivative) information was directly available from the peripheral display. Without the display, plant rate information had to be extracted from the motion of the foveal error display. Although the limitations to describing function calculations discussed in Chapter 5 resulted in limited low nominal frequency information, the Y_s data in Figs. 24 and 25 indicate that subjects were providing lead equilization at very low frequencies with the peripheral display present.

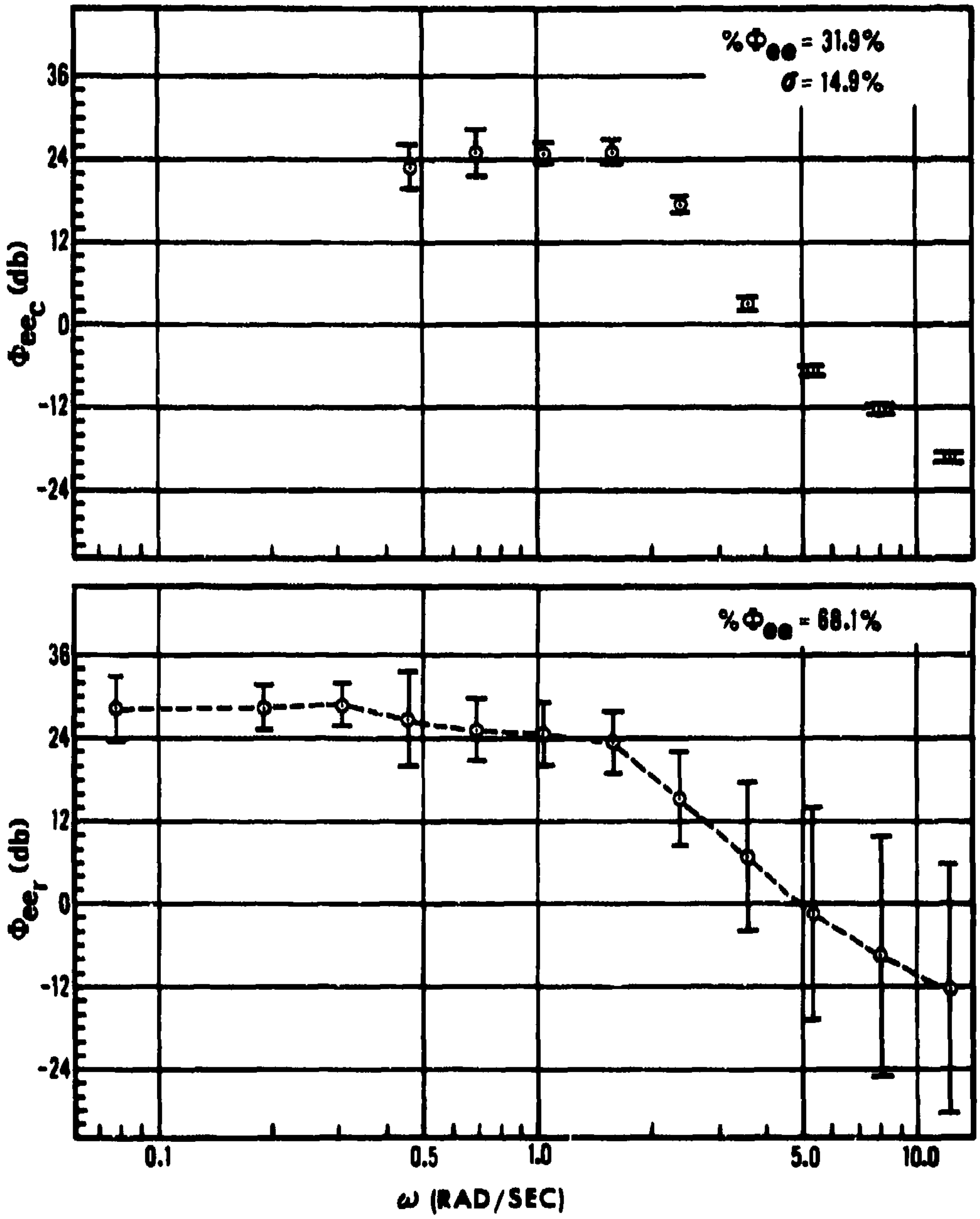

Figure 26. Averaged Group Error Power Spectra, Plant No. 2 the Controlled Plant - Without Peripheral Display

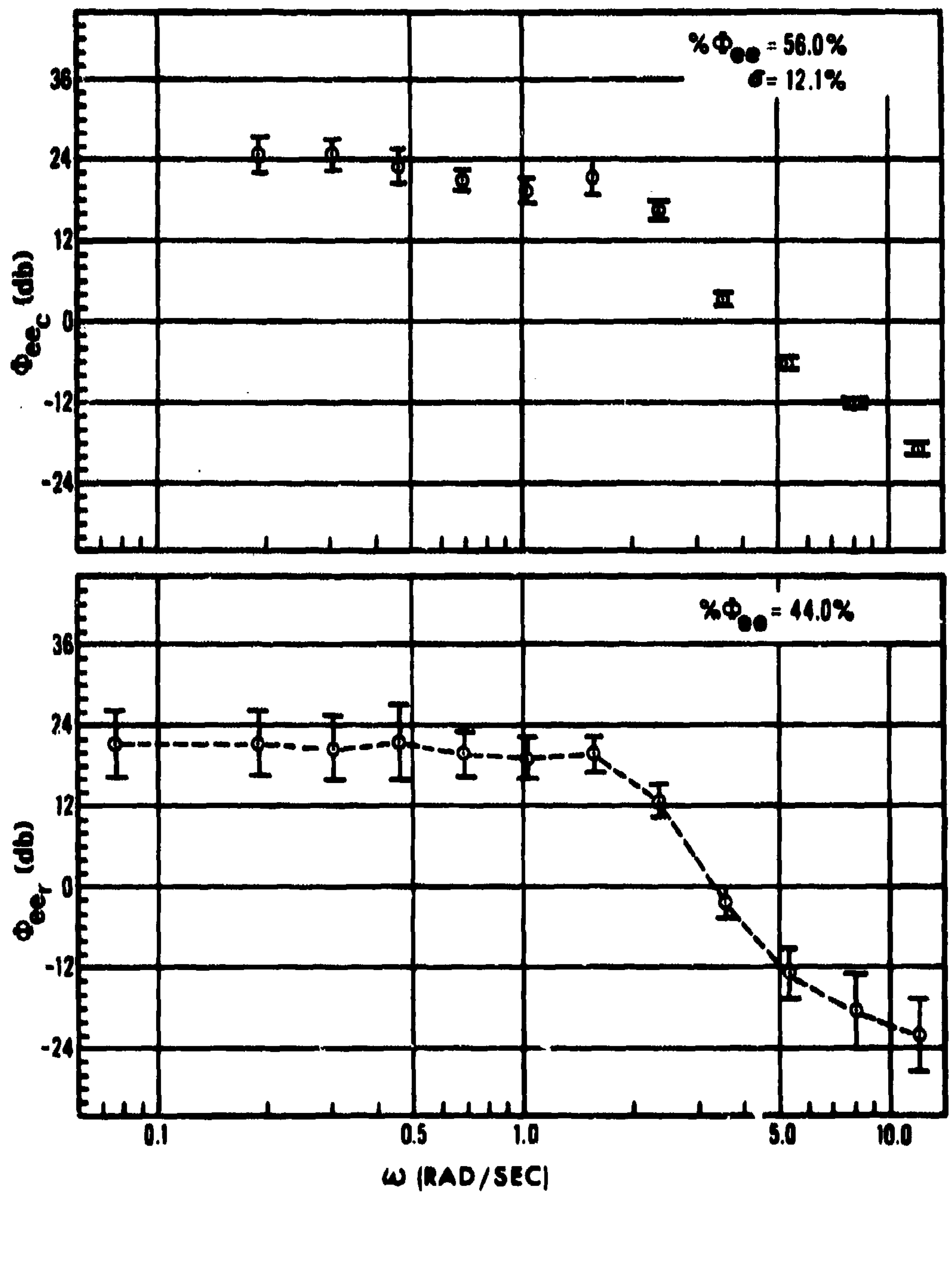

Figure 27. Averaged Group Error Power Spectra, Plant No. 2 the Controlled Plant - Peripheral Display Present

Averaged data at the nominal frequencies of $\omega = 0.307$ and $\omega = 0.460$ rad/sec reflect a 20 db/decade Y_s magnitude slope for subject correlated response when plant roll rate information was available from the peripheral display. The Y_s phase angle differences below ω_c and the uniformity of the Y_s magnitude data points above ω_c indicate that the major differences in subject performance, for the two experimental conditions, occurred at frequencies below $\omega = 1$ rad/sec. Insufficient data at low frequencies does not permit conclusive evaluation of the phase angle values to determine if human processing delays were different for the two experimental conditions or if the phase angle differences were strictly results of subject lag-lead equilization adjustments. Data comparisons discussed earlier, however, indicate that the significant difference in subject control responses for the two experimental conditions occurred at frequencies below gain crossover and the difference was due to lead generation (derivative compensation) at lower frequencies with the peripheral display present.

Subjective comments by the subjects revealed that their control strategy with the peripheral display present was to attain at or near-zero rate of movement of the display grid lines before attempting to minimize roll angle error. The subjects stated they used the peripheral display information "continuously" during their tracking task runs.

Fusion Speed and Peripheral Motion Threshold Effects

Fusion speed measurements were not precise enough to yield other than gross magnitude information. The lowest average fusion speed value for a given subject occurred for a plant roll rate of $\omega = 1.3$ rad/sec. The highest subject average was for a plant roll rate of 2.1 rad/sec. Plant roll rate corresponding to the group average fusion speed value was 1.75 rad/sec with a standard deviation of ±0.36 rad/sec. Describing function and error spectrum data do not indicate any conclusive evidence of fusion speed effect on subject performance.

Peripheral motion cue measurements were not attempted. A rough interpretation of Fig. 1 as applied to a peripheral viewing angle of 40° yields

$$V = r\omega$$

$$.16 \ \frac{\text{in.}}{\text{sec}} = 16.5 \text{ in.} \times \omega$$

$$\omega = 0.01 \text{ rad/sec.}$$

Certainly, the altimeter hand measurements are not directly applicable to the experimental conditions of this study. The distance to the peripheral display was 16.5 in. as opposed to 37.5 in. The altimeter hand measured 0.1 in. wide and 1.13 in. long; the peripheral grid lines were 2-3/4 in. wide. The implication is, however, that subject peripheral motion threshold for this experiment was well below the measurement band of frequencies.

VII. Conclusions and Recommendations

The conclusions presented in this chapter are related to a static human operator's performance of compensatory roll-axis tracking. Recommendations are given for additional research efforts necessary to identify limitations and possible operational uses of the type of peripheral vision motion cue investigated in this experiment.

Conclusions

1. For K/S^2-type controlled plant dynamics, roll-axis tracking performance of a static human controller is significantly improved when plant roll rate information, in the form of vertically moving black and white horizontal grid lines, is displayed in the peripheral field of vision.

2. Tracking performance is not significantly improved by displaying plant roll rate in the human operator's peripheral field of vision when the controlled plant is stable with control dynamics of the form K/S.

3. Peripheral display of controlled plant roll rate improves compensatory tracking performance when the controlled plant is of the general form of K/S^2 by providing the human operator instantaneous plant rate information which is necessary for successful control and which, otherwise, must be obtained by computing derivatives from the central error display. With plant derivative information provided, the human controller's computational workload is reduced, permitting a more precise response to any additional lead compensation

necessary to properly follow the input signal.

4. Plant roll rate displayed in the human controller's peripheral field of vision does not influence system gain crossover frequency. System phase margin is improved, however, for K/S^2 controlled plant dynamics due to improved low-frequency lead generation by the controller.

Recommendations

1. A similar roll axis compensatory tracking experiment should be conducted in which ambient lighting and display grid line height (viewing angle subtended) is varied. A study of this nature would define limits of practical application for the type of peripheral display used in this experiment.

2. Roll axis compensatory tracking tasks should be performed with the ratio of grid line linear velocity to controlled plant angular velocity increased, in steps, and the peripheral display positioned to stimulate different areas of the controller's peripheral vision. This study would permit better definition of optimum display scaling and would define permissible display locations in the peripheral vision field.

3. Investigations should be conducted to determine possible applications of the peripheral display to operational missions where controlled vehicle motion is not available to the operator. The display should be evaluated as an aid to maneuvering remotely piloted vehicles.

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Appendix A

Sum-of-Sines Input Forcing Function Frequencies

The tracking input signals used in this experiment consisted of 12 sinusoidal components which were harmonics of the base frequency $\omega_0 = 0.0383$ rad/sec. The sinusoidal component frequencies were (rad/sec):

$$
\begin{aligned}
\omega_1 &= 0.077\\
\omega_2 &= 0.192\\
\omega_3 &= 0.307\\
\omega_4 &= 0.460\\
\omega_5 &= 0.690\\
\omega_6 &= 1.035\\
\omega_7 &= 1.572\\
\omega_8 &= 2.378\\
\omega_9 &= 3.567\\
\omega_{10} &= 5.369\\
\omega_{11} &= 8.053\\
\omega_{12} &= 12.080
\end{aligned}
$$

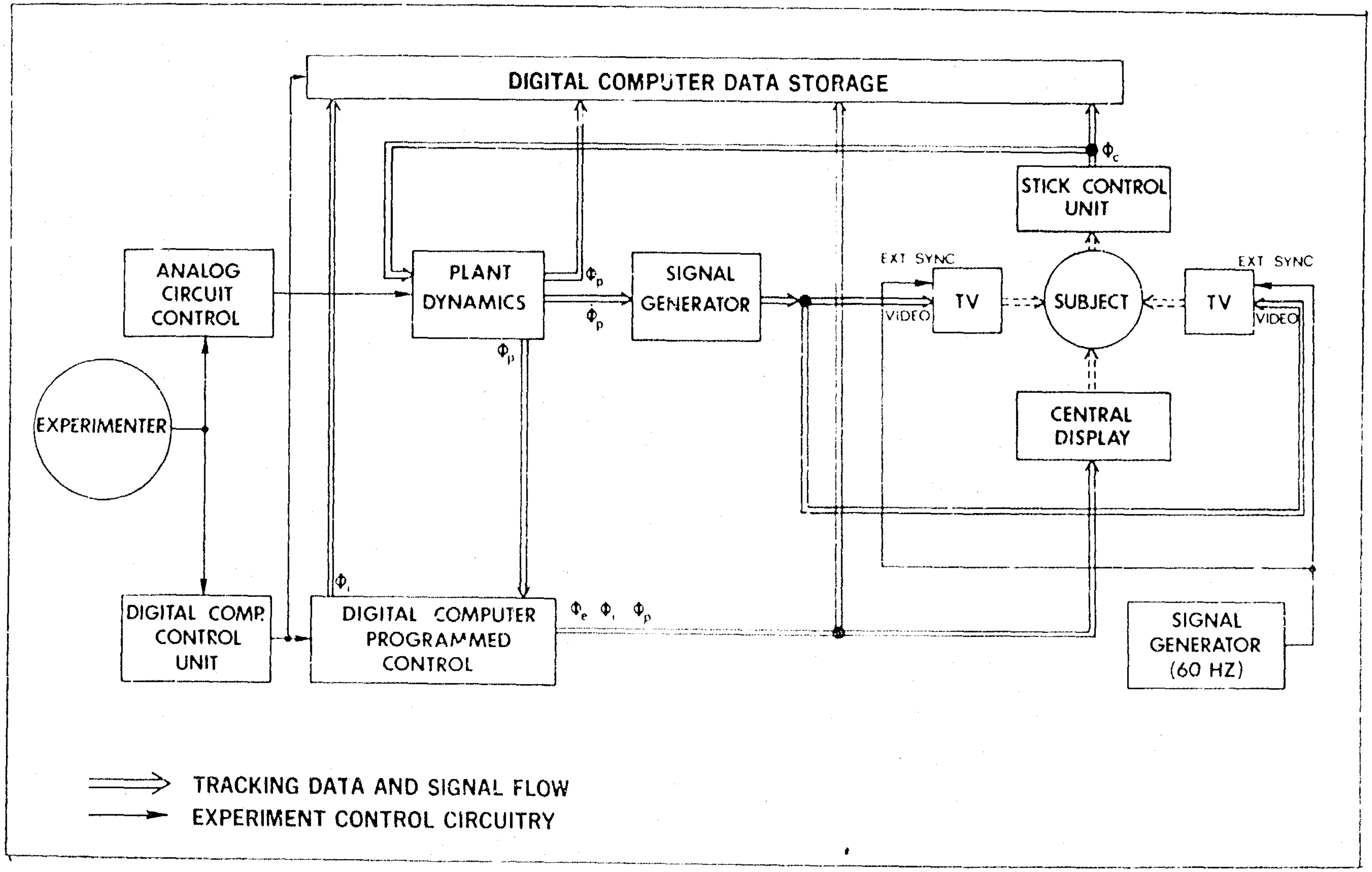

Figure 28. Appendix B: Experiment Hardware Implementation

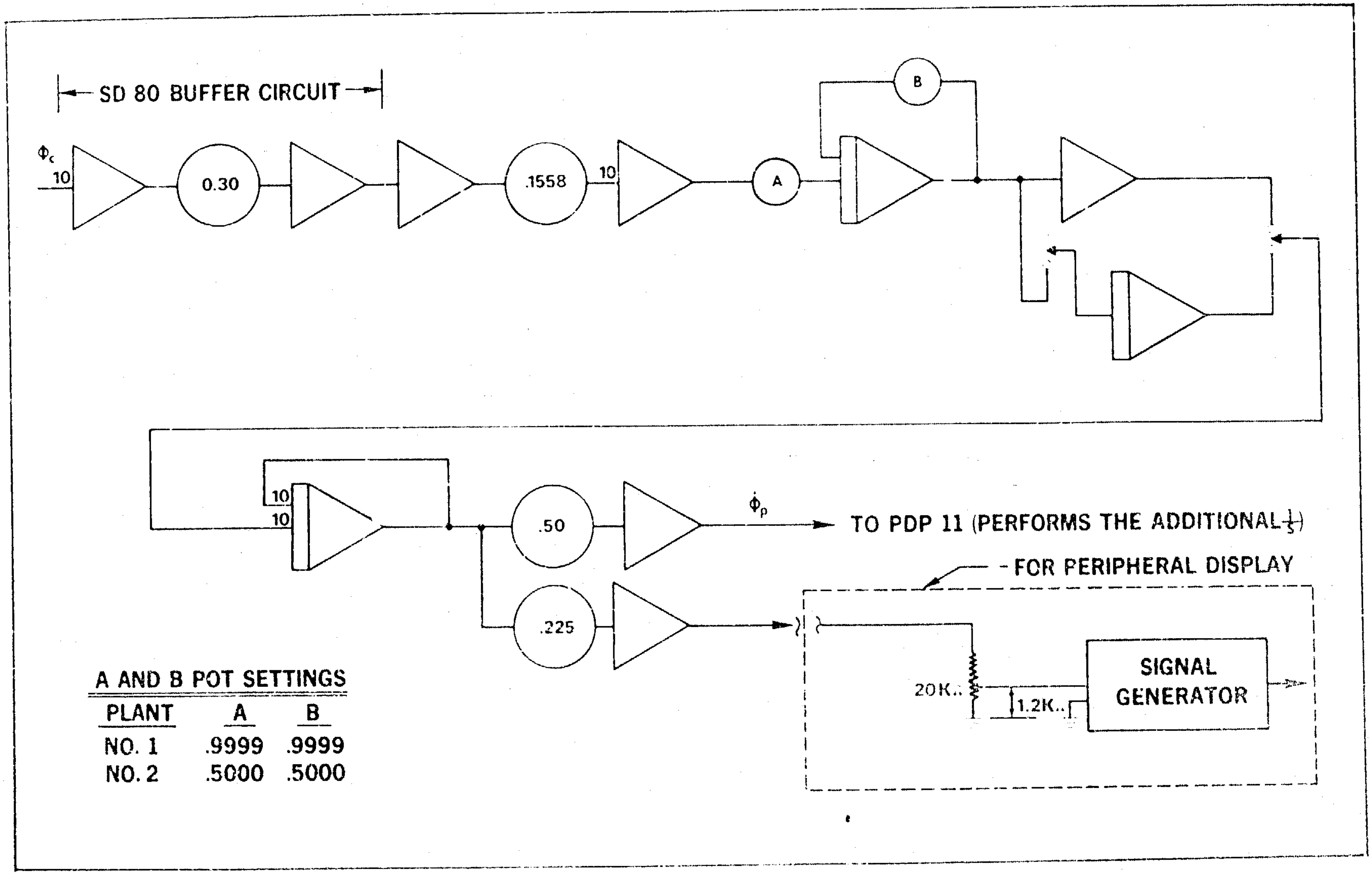

Figure 29. Appendix C: Analog Representation of Controlled Plant Dynamics

Appendix D

Subject Data

The subjects that performed the tracking runs were all college students, with the exception of the author. The peripheral vision field of each subject, with helmet on, was measured and the results are presented in Table II. Subjects who wore glasses were tested with their glasses on. Other subject information is presented in Table III.

The one subject (Subject BR) who was left-handed had previously participated in tracking experiments which employed the same right side-mounted force stick as the one used in this experiment. Subject BR stated that although she is left-handed, she does use her right hand for certain sports endeavors such as bowling. Subject BR's RMS error scores were consistently lower than the other members of the Plant No. 1 afternoon group. Her daily Plant No. 2 RMS error scores, both with and without the peripheral display, were generally the lowest or second lowest when compared with the other subjects performing the tracking runs with Plant No. 2 controlled plant dynamics. The author reasoned that Subject BR's performance was such that her results could be used in making group-averaged performance comparisons without biasing group data.

Table II

Subject Peripheral Vision Fields (Degrees) with Helmet On

Subject	Left	Right	Up	Down
RB	75	75	30	65
BD	70	75	30	55
EP	75	80	20	65
BR	65	65	25	60
DS	65	60	20	50
JF	75	80	30	55

Table III

Subject Physical Data

Subject	Age	Sex	Right or Left-Handed	Wears Glasses	Recreational Activities
RB	23	Male	Right	Yes	Motorcycling, Flying
BD	21	Male	Right	No	Basketball, Tennis
EP	22	Male	Right	Yes	Weightlifting, Flying
BR	20	Female	Left	No	Softball, Bowling
DS	20	Female	Right	No	Basketball, Track
JF	18	Female	Right	No	Ballet

Appendix E

Subject Briefings

Each subject was required to read a printed instruction sheet during their initial experiment briefing. The contents of the instruction sheet were as follows:

Description of Subject's Task

1. When you apply force stick pressure to the left or right you are "rolling" your simulated aircraft in the direction in which force stick pressure is applied.

2. Your task is to minimize the roll-axis angular difference between your aircraft and the target aircraft which is making random motions about the roll axis. The instantaneous angular difference is presented on the central display in the form of the aircraft symbol's rotational displacement from an upright wings level position. Therefore, you are to attempt to maintain the aircraft symbol in an upright wings level position at all times. This is accomplished by applying force stick pressure in the direction the aircraft symbol has rotated from the wings level position. You are perfectly aligned with the target when the aircraft symbol is upright and is superimposed on the stationary horizontal line of the central display.

Prior to performing the roll axis tracking task with peripheral displays present, each subject was familiarized with the peripheral display presentation. The subjects were required to read an instruction sheet concerning use of the peripheral display during the familiarization briefing. The printed instructions are presented on the following page.

Use of the Peripheral Display

1. During certain runs, horizontal black and white grid lines will be presented on each of two TV screens located on either side of the cockpit. These lines will move vertically in the direction stationary objects would appear to move if you were actually rolling the seat when force stick pressure is applied. For example, when applying pressure to the right, the grid lines on your right side will move upward and the grid lines on your left will move downward.

2. These peripheral vision motion cues are provided to give you a sense of the rolling motions of the aircraft you are "flying." Do not look at the peripheral displays; instead, fixate on the target display at all times. You should simply be aware of the type of information displayed on the TV screens in your peripheral field of view; and, with your peripheral vision, use the motion cue information in any manner which seems natural to assist you in accomplishing the tracking task.

Appendix F

Stick Signal Power Spectra

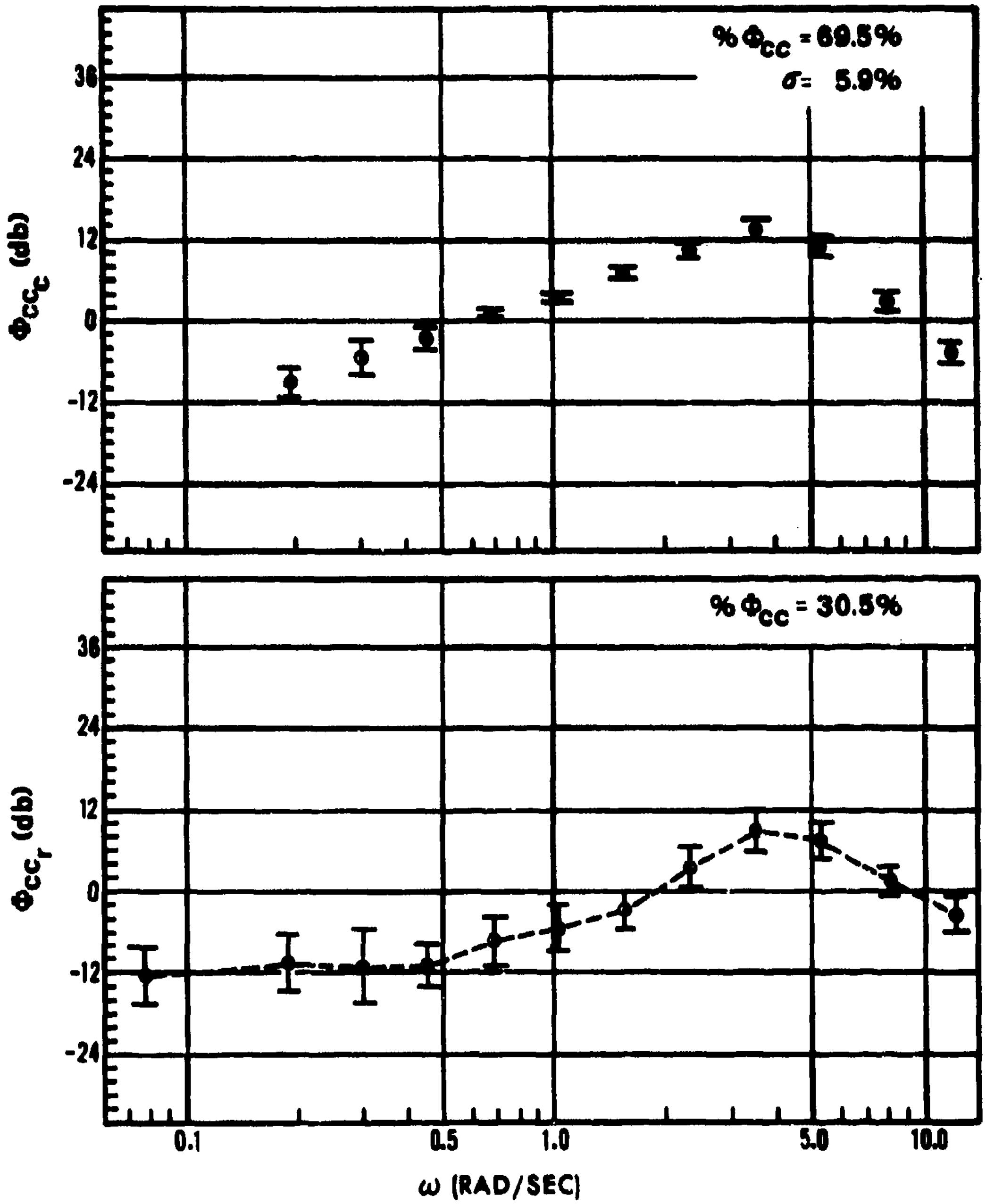

Figure F 1. Averaged Morning Group Stick Signal Power Spectra - Without Peripheral Display

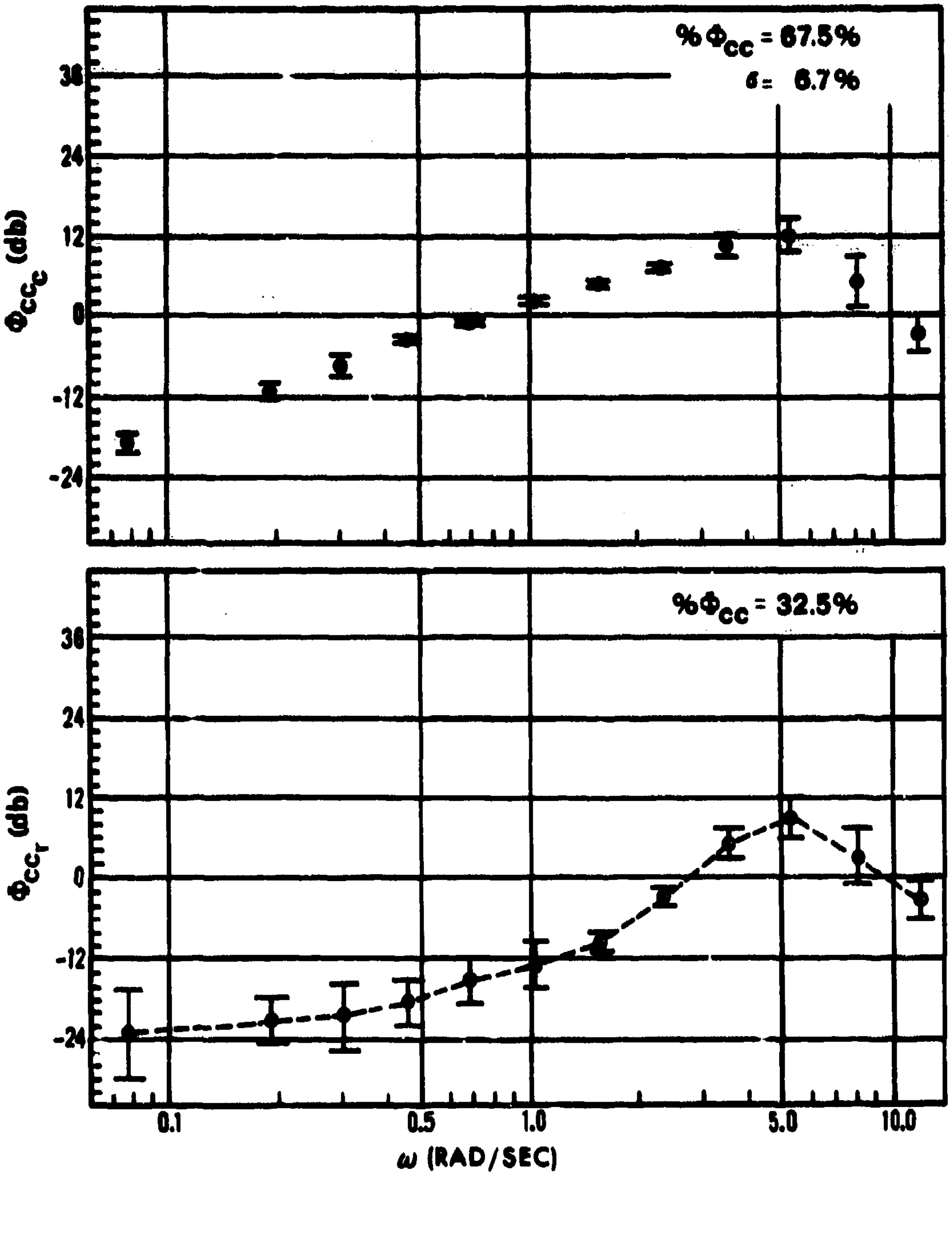

Figure F-2. Averaged Morning Group Stick Signal Power Spectra - Peripheral Display Present

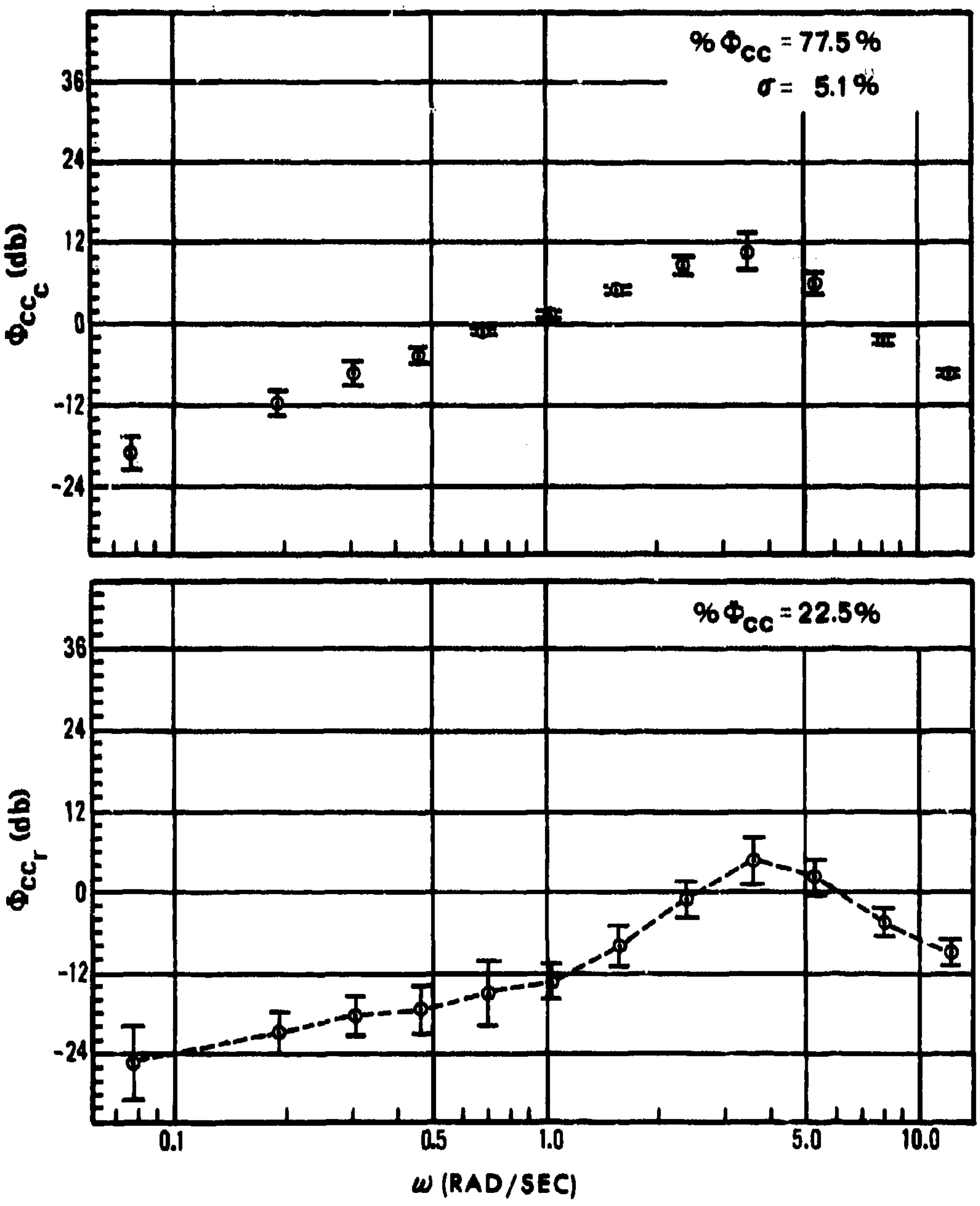

Figure F-3. Averaged Afternoon Group Stick Signal Power Spectra - Without Peripheral Display

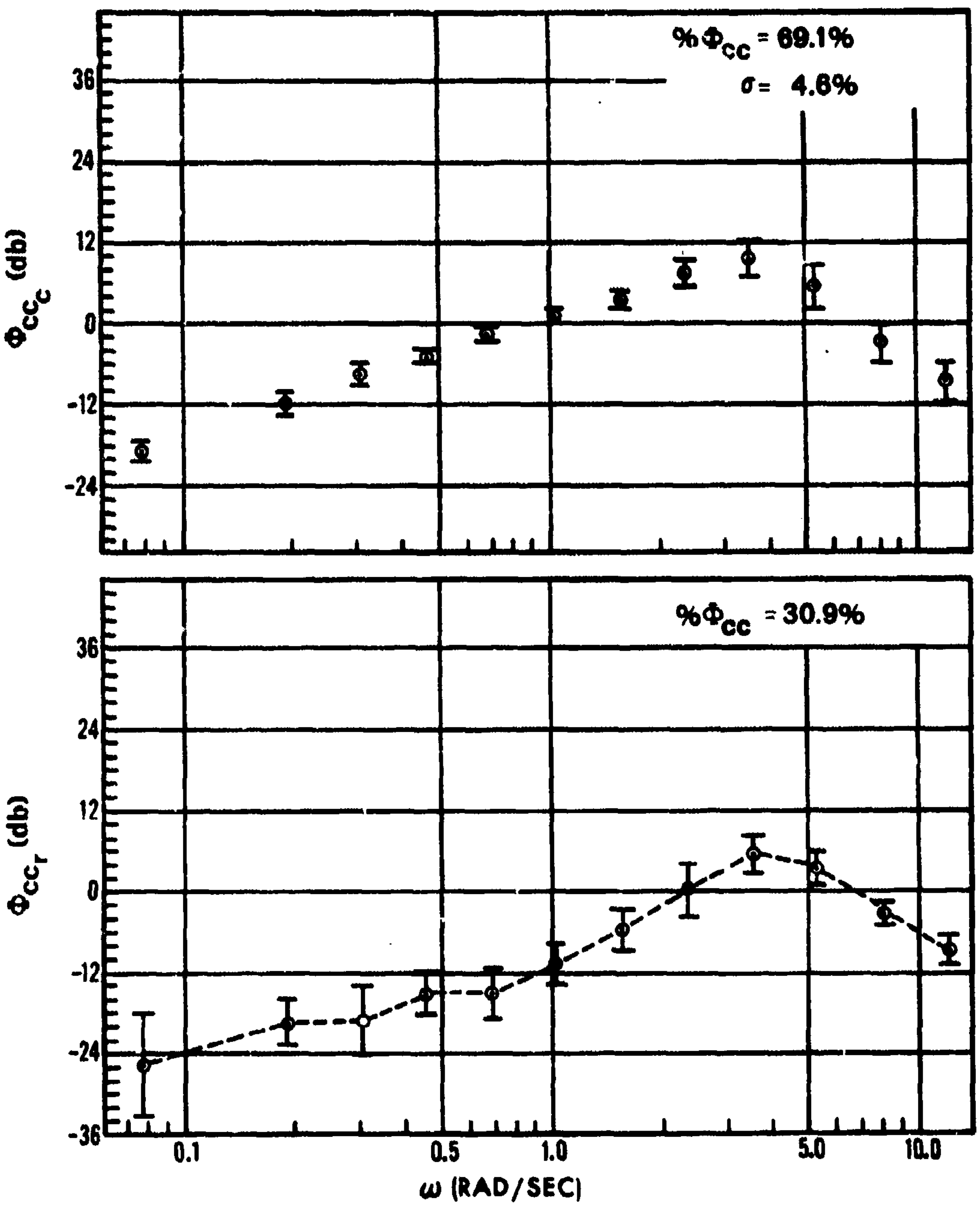

Figure F-4. Averaged Afternoon Group Stick Signal Power Spectra - Peripheral Display Present

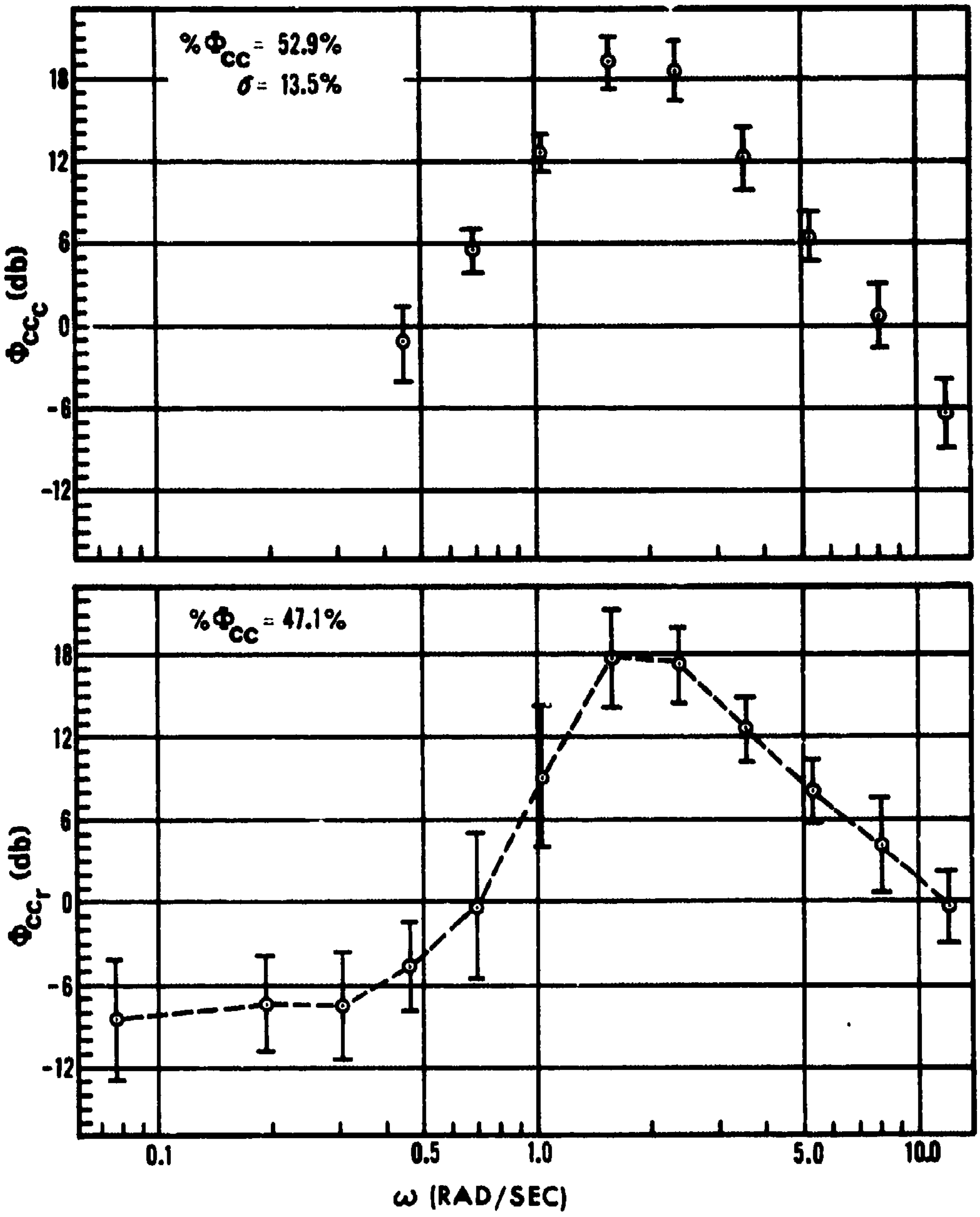

Figure F-5. Averaged Stick Signal Power Spectra, Plant No. 2 the Controlled Plant - Without Peripheral Display

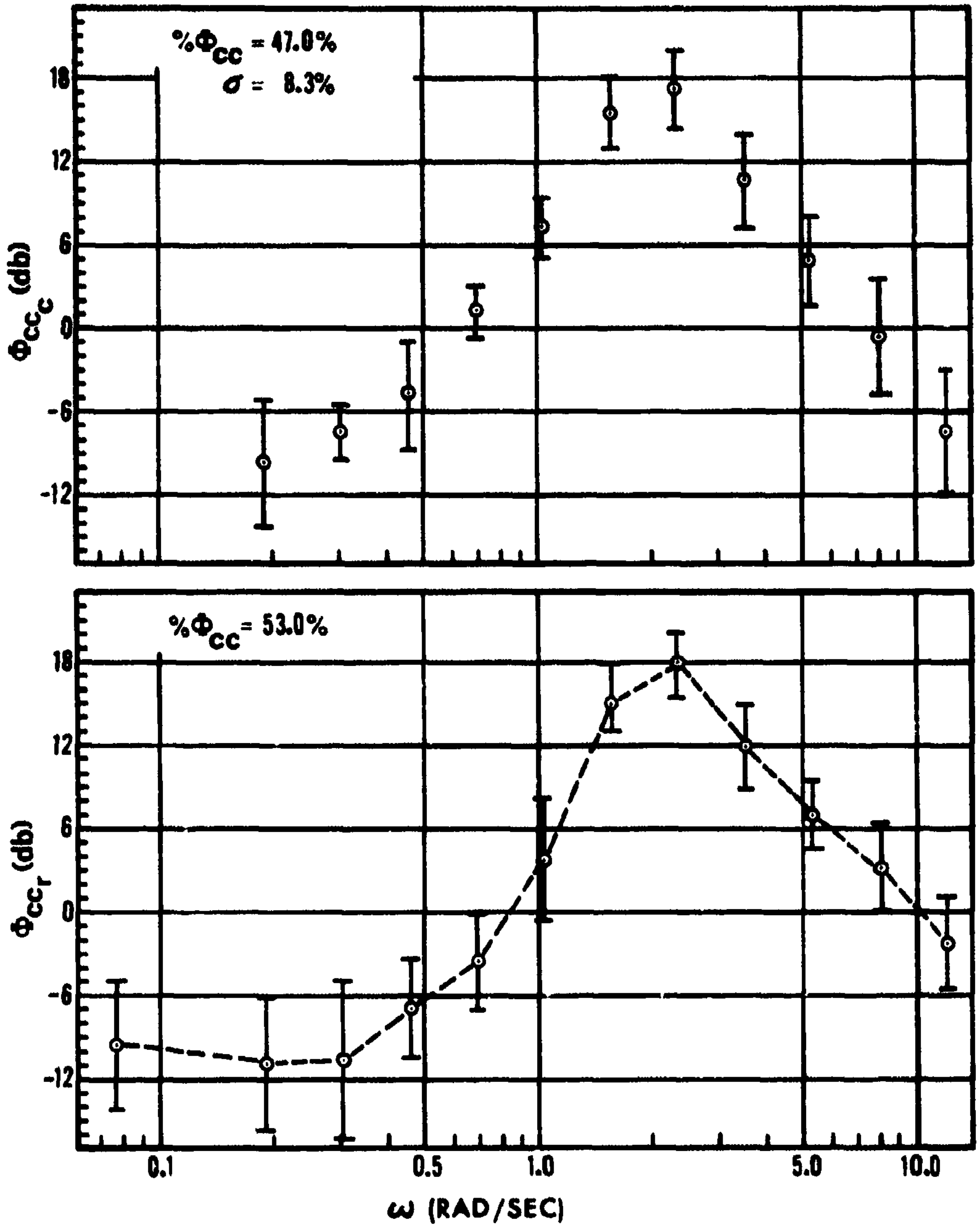

Figure F-6. Averaged Stick Signal Power Spectra, Plant No. 2 the Controlled Plant - Peripheral Display Present

Vita

Captain Don R. Price was born 17 December 1942 in Alexandria, Louisiana. He graduated from high school in Pollock, Louisiana in 1960 and enrolled at Louisiana Tech. He received the degree of Bachelor of Science in Electrical Engineering from Louisiana Tech in June 1965 and was commissioned a Second Lieutenant in the U.S. Air Force through the ROTC program. He received his pilot wings at Laredo AFB, Texas in September 1966 and was assigned to Davis-Monthan AFB, Arizona for F-4 training. Upon completion of training in July 1967, he reported to the 12th TFW at Cam Ranh Bay AB, RVN for a one year tour of duty. Subsequent F-4 assignments were at George AFB, California; Ubon RTAFB, Thailand; and Spangdahlem AB, W. Germany. His most recent operational duties were those of instructor pilot and wing maintenance quality control officer. He returned from Spangdahlem AB, W. Germany and entered the resident Graduate Electrical Engineering program at AFIT in June 1974.

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